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D1.1 ICARIA HOLISTIC MODELLING FRAMEWORK

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101093806.

D1.1 ICARIA holistic modelling framework

Summary

The ICARIA holistic modelling framework, outlined in Deliverable 1.1, defines the procedure to achieve a comprehensive risk/impact assessment across different climate-related hazard categories, also covering complex interactions characterised by compound events and cascading effects, in the context of climate change. Although implemented and validated through ICARIA Trials and Mini-trials for the Barcelona Metropolitan Area, South Aegean Region, and Salzburg Region case studies, the framework is conceived to be exportable to any other EU region potentially affected by such events. Indeed, it provides a consistent and harmonized methodology to build climate scenarios, collect available and usable modelling data, fill any related gaps and/or uncertainties, perform exposure/vulnerability analyses, assess risk/impact and understand how climate scenarios might affect critical assets and services involved. Indeed, the holistic modelling framework also facilitates the evaluation of possible direct and indirect damage (including cascading effects) to different risk receptors, with the aim of providing suitable, sustainable and cost-effective adaptation solutions supporting decision-makers, in order to ensure that complex socio-eco-technological systems can improve their resilience level.

Therefore, given the considerations above, this document represents the primary reference for both the ICARIA project development and attainment of its associated objectives and sub-objectives.

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D1.1	WP1

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Document history

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30/11/2023	1.6	Agnese Turchi (UNINA) Mattia FedericoLeone (UNINA)	Final version of the deliverable. All suggestions have been considered and applied.

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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 ICARIA holistic modelling framework and outlines the overall risk/impact assessment methodology from a multi-hazard perspective, ensuring consistency across all identified climate-related hazards categories (i.e., heat waves, forest fires, droughts, floods, storm surges, and storm wind) and guaranteeing the alignment with prevailing EU and International frameworks and metrics for risk/impact assessment in the context of climate change. In this sense, the document aims to define the most significant aspects for which building climate scenarios, collecting essential modelling data, performing the exposure/vulnerability assessment for critical assets (e.g., infrastructures) and services (e.g., related to urban water, transport, energy, waste, natural areas, and tourism sectors) at risk, until reaching the overall risk/impact assessment. It also aims to guarantee that both the data and models used to estimate local hazard conditions and anticipate related repercussions (tangible direct and indirect damage, including cascading effects) on risk receptors are sensitive to any possible transformation of those assets and services. The link between the implementation of resilience measures at the urban scale and the potential risk reduction benefits for civil society, key-stakeholders, and authorities is the focal point of the document.
Therefore, it represents a comprehensive guidance as well as a reference to develop and execute most of the ICARIA project activities by the Consortium.

The document primarily highlights the importance of having a holistic modelling framework aimed at multi-hazard risk/impact assessment, to both achieve a better understanding of any possible repercussions on exposed elements and define suitable, sustainable and cost-effective adaptation solutions (Section 1), from a “climate resilient development” perspective. Secondarily, it highlights the urgency to move from a “vulnerability-oriented” to a “risk-based” approach to the climate impact analysis, which also includes the integration of the so-called resilience determinants of Coping Capacity, Adaptive Capacity, and Transformative Capacity (Section 2) to have a truly all-encompassing modelling framework. Therefore, Section 2 identifies differences between single-hazard and multi-hazard risk/impact assessment, paying attention to time and space interdependencies, clarifies taxonomies behind the framework and related “elementary bricks”, and proposes potentially quantifiable resilience metrics. Finally, the document describes each case study region involved (i.e., Barcelona Metropolitan Area, South Aegean Region, and Salzburg Region) in terms of geographical location, climate hazards, risk receptors, and expected impacts in order to correlate the ICARIA holistic modelling framework and the Trial and Mini-trial phases (Section 3). Section 3 also identifies possible modelling gaps and uncertainties that primarily affect the data collection.

1. Introduction

This document presents the *comprehensive 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 1.1 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 stays 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 1.1

In the ICARIA project, Task 1.1 aims at defining a harmonized and consistent holistic modelling framework supporting impact and resilience assessments across different climate-related hazard categories. The framework aims at providing a methodology to build climate scenarios, collect required modelling data and fill related gaps/uncertainties, perform exposure/vulnerability analyses, assess the overall risk/impact and thus develop resilience pathways that enable providing a set of adaptation solutions supporting decision-makers (Russo *et al.,* 2023). Based on a multi-hazard approach (Kappes *et al.,* 2012; Marzocchi *et al.,* 2012) that covers complex interactions characterised by compound events and cascading effects [Pescaroli & Alexander, 2018; Alexander, 2021], the methodology ensures that data and algorithms used to determine local hazard conditions and expected impacts on exposed elements are responsive to possible transformations of critical assets (e.g., the critical infrastructure of the services under assessment, namely infrastructure components, properties etc.) and services related to urban water, transport, energy, waste, natural areas and tourism sectors. Furthermore, tourism is considered an important variable as on the one side it can influence the level of risk/impact (e.g., increased tourism increases water supply demands, thus increasing vulnerability to droughts; it also increase energy demands thus increasing vulnerability to heat waves), on the other it can be influenced by the occurrence of one or more hazardous events (e.g., civil society organizations prevent usage of bathing areas, thus reducing tourism). In this sense, the methodology allows to correlate the implementation of suitable, sustainable and cost-effective resilience measures with the potential benefits of risk reduction.

The framework, presented in Deliverable 1.1, defines step-by-step the modelling process to be followed for all the targeted climate-related hazards (i.e., heat waves, forest fires, droughts, floods, storm surges, and storm wind) affecting case study (CS) regions identified within the project (Barcelona Metropolitan Area, South Aegean Region, and Salzburg Region), in order to achieve a comprehensive impact/risk assessment for ICARIA Trials and Mini-trials. As a matter of fact, both the implementation (Trial) and replication (Mini-trial) phases are used to test the methodology and technical solutions, with the purpose of gradually covering several aspects of risk/impact assessment (e.g., minimum requirement in terms of input data needed to analyse climate hazards and related impacts on critical assets, effects of possible adaptation solutions, optimization of the interaction between climate change, climate adaptation and society through solid decision support, and many others). Therefore, the document provides an exhaustive characterisation of Hazard, (H) Exposure (E), Vulnerability (V), Dynamic Vulnerability (DV), and Damage (D) that represent the main so-called “elementary bricks” of the framework (Zuccaro *et al.,* 2018). Considering the role of Time (t) and Space (s) dimensions, this document mainly targets differences between single-hazard and multi-hazard risk/impact assessment approaches and tries to holistically incorporate into the framework Coping Capacity (CC), Adaptive Capacity (AC) and Transformative Capacity (TC), influenced by the Human behaviour (α) variable, with the purpose of parameterising and quantifying them as main resilience components (Turchi *et al.,* 2023a).

The service-oriented methodology behind the framework aims at maximising the exploitation of existing modelling data and methods to handle related gaps/uncertainties. It has been designed to consider i) the impacts of adaptation measures on the local hazard conditions, exposure and vulnerability, and ii) the post-processing of modelling results through Cost-Benefits Analysis (CBA) and Multi-Criteria Analysis (MCA) tools as Decision Support System (DSS) components. Consequently, the methodology focuses on how model contextual features of hazards and all those precursor conditions that aggravate them, as well as their relations, identifying the trigger mechanism of cascades. Furthermore, it focuses on the spatial distribution of the elements at risk, classified according to their intrinsic characteristics, and related vulnerability functions. Finally, the methodology links quantitative impact modelling results with post-processing tools for CBA analyses within DSS, with the scope of prioritising adaptation solutions in relation to their social, environmental, and economic co-benefits.

The objectives of D1.1 can be summarised as follows:

- clarify taxonomies behind the ICARIA holistic modelling framework;
- remark differences between single-hazard and multi-hazard risk/impact assessment approaches, paying attention to time and space interdependencies (focus on complex interactions, such as compound events and cascading effects);
- explain how to introduce resilience components within the framework, identifying potentially quantifiable CC, AC and TC metrics;

- define the correlation between the theoretical ICARIA holistic modelling framework and the implementation of Trial and Mini-trial within each CS region;
- identify any possible modelling gaps/uncertainties, which primarily affect the data collection phase.

2. Holistic modelling framework

2.1. From a single-hazard to a multi-hazard risk/impact assessment approach

The risk/impact assessment related to meteorological extremes has been historically addressed by analysing each hazard individually, one at a time (Russo *et al.,* 2023). The single-hazard approach has so far limited the development of a comprehensive, harmonized and integrated modelling framework based on a multi-hazard risk/impact assessment approach and capable to holistically understand the weight of climate impacts on complex socio-eco-technological systems as well as define possible climate resilient pathways (Zuccaro & Leone, 2018; Turchi *et al.,* 2023a). The number of climate-related disasters has progressively increased over the last twenty years and this trend will get worse in mid- and long-term because of the effects of global warming and related climate change (Velasco *et al.,* 2020). This increase often manifests itself through the occurrence of complex interactions, characterised by compound events (e.g., floods and landslides, triggered by heavy rainfalls) and cascading effects (e.g., forest fires fuelled by persistent drought, triggered by heat wave conditions) whose impacts, resulting from such multi-hazard conditions, might be greater than the sum of the effects of individual hazards (Hochrainer-Stigler *et al.,* 2023; Kappes *et al.,* 2012). In this perspective, a paradigm shift towards an effective multi-hazard risk/impact that includes resilience assessment is required (Kappes *et al.,* 2012; Zscheischler *et al.,* 2018; Ward *et al.,* 2022). Indeed, this would rise the consciousness on the interconnection between different hazards with respect to observed and projected climate trends, the multi-sectoral consequences of complex hazard/impact scenarios thus taking into account compound and cascading conditions and interactions, and the cost-effectiveness of resilience measures (organizational, spatial, functional and physical) targeting more than one hazard.

The multi-hazard risk/impact assessment starts from the assumption that the combination of multiple climate events and/or drivers puts society, assets, services, environment, etc. at risk in a combined manner. Depending on how the combination of these events occurs over time and space, receptors will suffer more severe damage than they would if a single event occurred, and the nature of damage will vary depending on both the complexity and interdependencies between hazards and/or impacts involved (Kappes *et al.,* 2012; Zscheischler *et al.,* 2018; Zuccaro *et al.,* 2018; Ward *et al.,* 2022). Understanding the implications of compound events (whether coincident or consecutive) on specific categories of risk receptors – and of cascading effects arising from the propagation of impacts across assets and services – is the starting point to develop an asset-level modelling framework that effectively supports and orients decision-making processes towards the identification and assessment of strategies and measures to improve resilience.

The Intergovernmental Panel on Climate Change (IPCC) operated a significant shift from a “vulnerability-oriented” (AR4) to a “risk-based” (AR5) approach to the climate impact assessments (Murieta *et al.,* 2021, Connelly *et al.,* 2018), where the second one represents the conventional approach borrowed from the risk sciences and emergency management (UNDRO, 1980; UN-DHA, 1993; Coburn *et al.,* 1994) and widely applied for geophysical events (e.g., earthquakes, volcanic eruptions, tsunamis, etc.), thus helping to reduce the existing distance between the Disaster Risk and the Climate Change scientific communities through the combination of methods and approaches from risk and emergency management sciences with those from earth and environmental sciences. The Fifth Assessment Report (AR5) (IPCC, 2014) already reaffirmed the centrality of risk factors (hazard, exposure and vulnerability) as key-variables. Concerning climate events, this shift gives the possibility of identifying adaptive strategies and measures in relation to the magnitude of impacts (direct and indirect damage, including cascading effects), while also addressing any potential uncertainty inherent to the ongoing climate crisis (Sainz de Murieta *et al.,* 2021; Turchi *et al.,* 2023a). The Sixth Assessment Report (AR6) (IPCC, 2022) confirms the AR5 risk-based approach, but further highlights how the growing impacts of climate change require the definition of an integrated strategic approach to adaptation and mitigation (IPCC AR6 WG I) based on specific and complementary actions in different sectors that promote the development of climate resilient pathways capable of contributing locally to the achievement of the Sustainable Development Goals (SDG) (IPCC AR6 WGII). These aspects are particularly relevant when considering the critical metrics for resilience assessment, which expands beyond specific indicators measuring the Impact reduction potential of targeted measures to capture their contribution in terms of Greenhouse Gases (GHG) emissions reduction and the related social, environmental, and economic co-benefits.

In parallel, the evolving nature of reference documents and technical guidance from the European Commission addressing climate resiliency (e.g., European Commission, 2011), adaptation (e.g., European Commission, 2023) and climate proofing (e.g., European Commission, 2021) orients the methodological framework adopted in specific projects funded by the EU.

In particular, the hazard/impact (and adaptation/resilience) assessment frameworks developed in relevant EU H2020 projects constituting the core scientific background adopted in ICARIA, such as the RESCCUE projects (RESCCUE, 2016; FIGURE 1) and the CLARITY project (CLARITY, 2017; FIGURE 2) show some apparent discrepancies in the identification of analytical components associated to modelling and assessments.

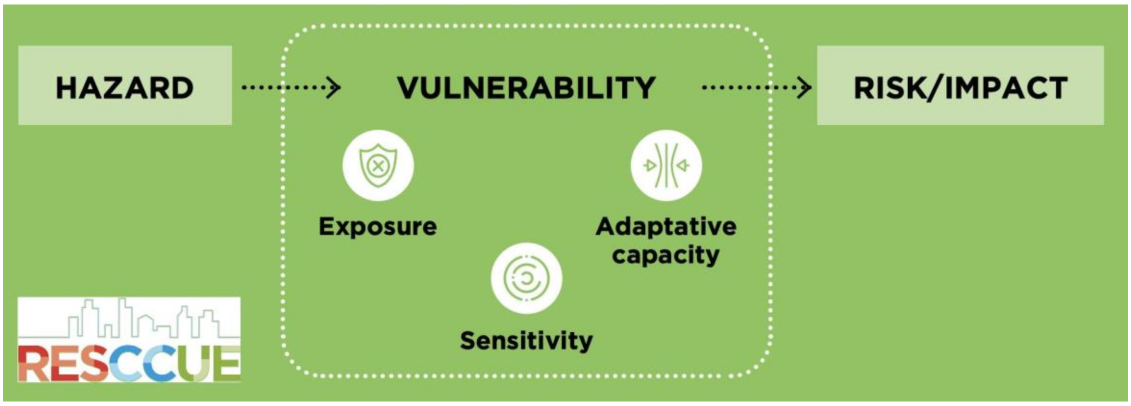


Figure 1. The risk/impact assessment framework adopted in the context of the RESCCUE project, based on the IPCC AR4 approach (RESCCUE Guidelines, 2016).

Figure 2. The risk/impact/adaptation assessment framework adopted in the context of the CLARITY project, based on the IPCC AR5 approach and following the European Commission guidelines for project managers on how to make vulnerable investments climate resilient (2011) (de Wit *et al.,* 2020).

A more detailed analysis of theoretical framework and modelling approaches (see e.g., Evans *et al. (*2017) and Goler *et al.* (2019)) highlights the consistency of approaches for what concerns the "elementary bricks" (see Section 2.1.2) involved in the modelling workflow. As an example, the "sensitivity" concept highlighted in the RESCCUE scheme is embedded in the notion of "vulnerability" within CLARITY and linked to the "hazard local effect" characterization (in line with IPCC, 2014 and IPCC, 2022, see Zuccaro and Leone, 2021). Similarly, the "exposure", highlighted in the CLARITY scheme, is embedded in the notion of "vulnerability" (also in continuity with the approach of the EU H2020 BINGO project, as reported by Rocha *et al.,* 2017).

In the scope of ICARIA project, the risk/impact assessment framework is designed to enable the evaluation of resilience components as part of the modelling workflow, in line with the most recent conceptualization developed by IPCC in AR6 (FIGURE 3; IPCC, 2022), which emphasize how resilience (i.e., the "climate resilient development" strategies and measures) interacts with Hazard, Exposure and Vulnerability, recognized as the three critical components of risks/impact assessment.

The compliance between the proposed framework and the approaches highlighted by the latest cross-sectoral technical guidance available at EU level (2021/C 373/01; European Commission, 2021) is underlined by the guidance itself, which "permits the use of alternative approaches to the described climate vulnerability and risk assessment that are recent and internationally recognised approaches and methodological frameworks, for instance the approach applied by the IPCC in the context of the 6th Assessment Report [...]. The aim remains to identify significant climate risks as the basis for identifying, appraising and implementing targeted adaptation measures" (European Commission, 2021). It is important to note that the more recent technical guidance (European Commission, 2023), only limited to the building sector, while widely incorporating core content from the European Commission 2021 concerning the general framework definition and the suggested operational procedures for vulnerability and risk assessment, deliberately exclude the above-reported paragraph, thus introducing significant divergence elements with respect to the key messages and findings from IPCC, 2022 (including completely missing the conceptual, methodological and operational consequences from the introduction of the crucial concept of "climate resilient development").

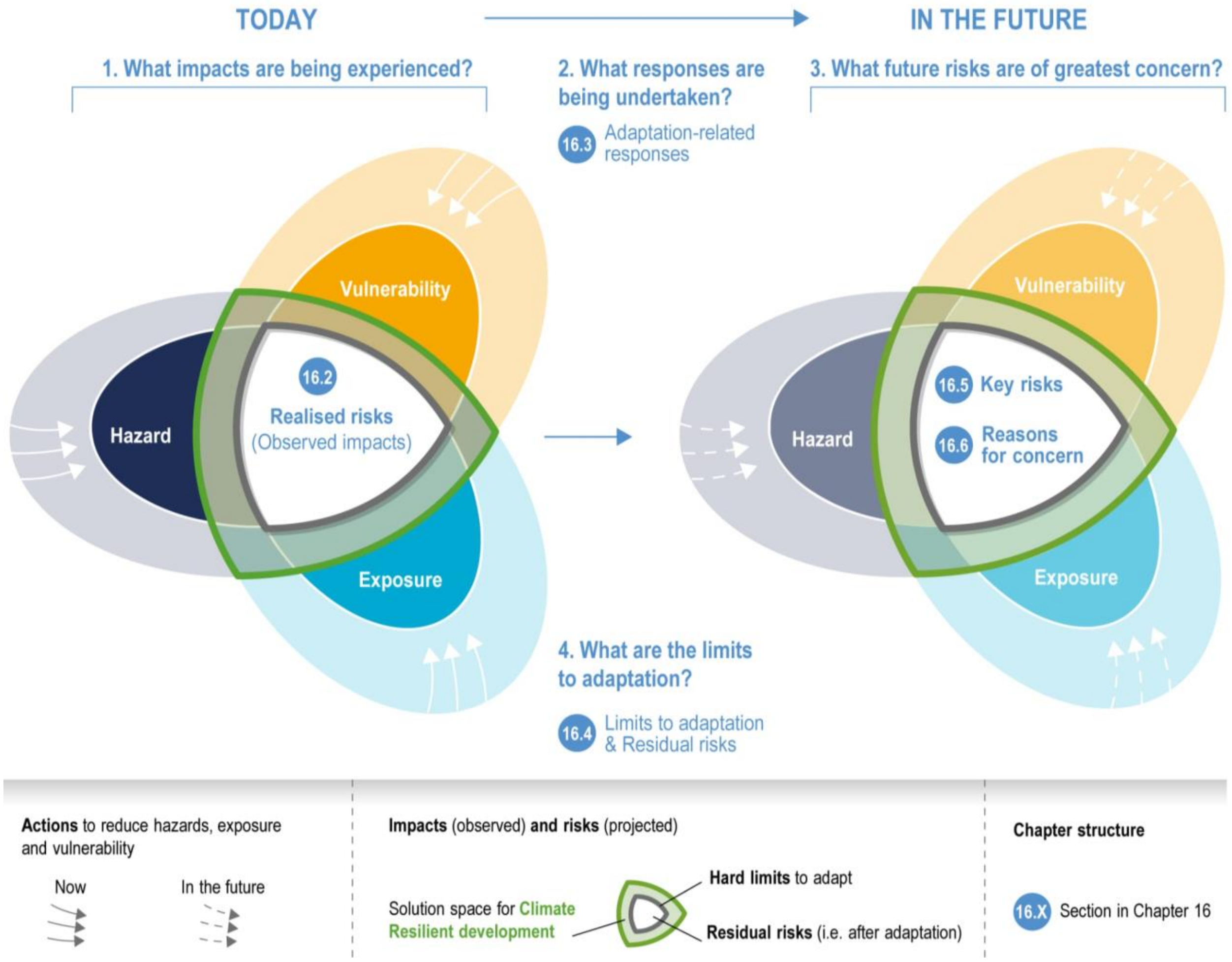


Figure 3. Conceptual framework for climate risk/impacts assessment and "climate resilient development" implementation (IPCC, 2022).

On the other hand, the European Commission 2021 technical guidance has been incorporated in the EU 2021-2027 cohesion policy framework and thus directly impacting member states regulation and operational procedures to access and account EU fundings under the European Green Deal, including the European Regional Development Fund (ERDF), the Cohesion Fund (CF), the European Social Fund Plus (ESF+) and the Just Transition Fund (JTF). The Common Provisions Regulation (CPR) (European Parliament, 2021) lays down common rules for these and a number of other EU funds, which are also being extended by member states to the management of funding under the REACT-EU programme (which provides additional resources for mitigating the effects of the coronavirus pandemic). The new concept of climate-proofing, associated with the social, economic and environmental goals of the specific funding programmes directly connects to the IPCC "climate resilient development" approach highlighting that "adequate mechanisms to ensure the climate-proofing of supported investment in infrastructure should be an integral part of programming and implementation of the funds (recital 10 of the CPR)" and that, in selecting interventions to be funded, the managing authorities must "ensure the climate proofing of investments in infrastructure which have an expected lifespan of at least 5 years" (Article 73 of the CPR).

The need of preventing "infrastructure from being vulnerable to potential long-term climate impacts whilst ensuring that the 'energy efficiency first' principle is respected and that the level of greenhouse gas emissions arising from the project is consistent with the climate neutrality objective in 2050" (Article 2 of the CPR), translates in the obligation for managing authorities of accounting and quantifying the benefits in terms of resilience – integrating climate benefits in terms of mitigation and adaptation and the social, economic and environmental co-benefits in line with EU Taxonomy – thus highlighting the relevance of quantitative methods to assess resilience capacities associated to infrastructure development.

While most currently used resilience indicators are of qualitative nature (Leischenko, 2011; Chelleri, 2012; Chelleri *et al.,* 2015; Meerow *et al.,* 2016; Meerow & Newell, 2019; Turchi *et al.,* 2023), ICARIA intends to introduce evidence-based quantitative metrics representative of governance structures, planned policy actions for increasing citizens' risk awareness, or tools/instruments available to local stakeholders within a the proposed holistic modelling framework (Leischenko, 2011; Chelleri, 2012; Chelleri *et al.,* 2015; Meerow *et al.,* 2016; Meerow & Newell, 2019; Turchi *et al.,* 2023). In this regard, the ICARIA risk/impact assessment framework integrates critical resilience components in the modelling workflow. In this perspective, metrics and indicators developed within Task 3.2 - Holistic Resilience Methods (see D3.2) have been analysed to identify those potentially measurable through quantitative methods.

Figure 4. Four stages of DRM cycle (modified after Garn *et al.,* 2023 and Zuccaro *et al.,* 2018).

Understanding the impacts of combined climate hazards on complex socio-eco-technological urban and territorial systems is a key priority to identify measures aimed at increasing both the coping and adaptive capacity in local contexts. Within the framework, the concept of "transformative capacity" is added (see Section 2.1.2) to reflect evolutionary resilience approaches aimed at implementing effective climate resilient pathways in line with the AR6 framework. This requires that resilience components are integrated in the risk-based approach defining the corresponding quantitative metrics supporting the integration of resilience pathways within the full Disaster Risk Management (DRM) cycle (FIGURE 4) (UNISDR, 2015; Zuccaro *et al*., 2017; Schipper *et al.,* 2022; IPCC, 2023).

In the ICARIA framework the resilience assessment is directly connected to the impact scenario analysis by performing an "alternate run" of the relevant hazard/impact models with resilience measures in place, so as to evaluate their effects on reducing impacts.

Within ICARIA, the types of impacts caused by climate events are classified as tangible and intangible. Both, in turn, can be categorized as direct or indirect (Velasco et al., 2016). The common practice in risk sciences and emergency management is to divide risk impacts into economic and non-economic losses associated with direct and indirect risk, respectively. Economic losses can be easily understood as the loss of resources, goods and services typically exchanged in markets, with their valuation often determined by market prices serving to assess their value. Non-economic losses are more difficult to assess since they can be considered as non-economic items not commonly traded in markets, sometimes known as “intangible losses” with an effect on human welfare as important as the economic losses (UNFCCC, 2013). This is why a comprehensive evaluation of all direct, indirect, and intangible losses would produce much higher loss estimates than those related to direct loss records (generally easier to quantify).

The general conceptualization of the ICARIA risk/impact/resilience assessment framework is presented in FIGURE 5.

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 2.1.2);
- 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 in vulnerability classes and highlighting organizational, physical, spatial and functional interdependencies with other assets/services;
- Vulnerability: developing vulnerability functions associating for each of the asset (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 quantifying 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.

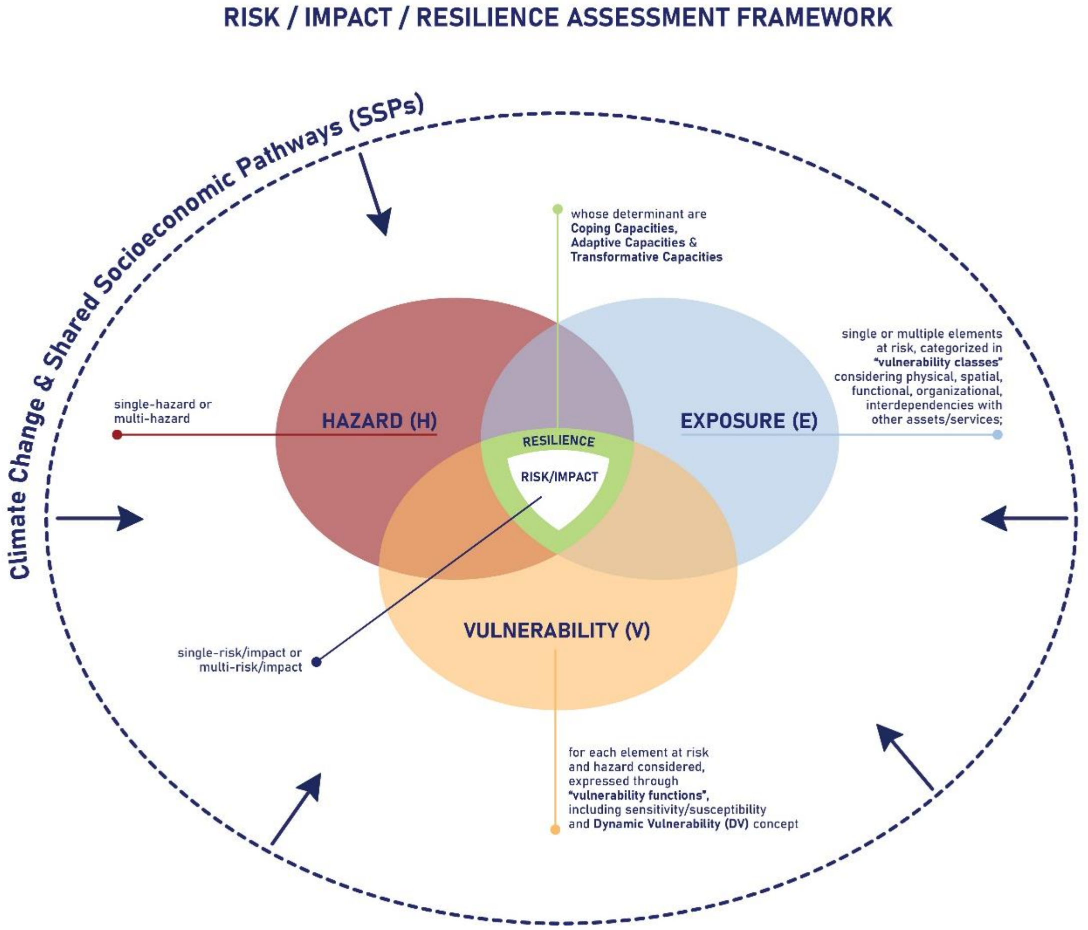


Figure 5. The risk/impact/resilience assessment framework, consolidated in the field of geophysical hazards (UNDRO, 1980; updated by the UNDRR, 2017 terminology) and harmonized in the context of climate change (IPCC, 2014; IPCC, 2022) introducing the resilience components (modified after Leone, 2020a 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 2.1.3).

In summary, a complex compound events and cascading effects scenario assessment 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. This quantification should also consider the coping, adaptive and transformative side of resilience, which further influence the system's response to combined events.

Therefore, the ICARIA modelling workflow is based on the following general methodological steps:

1) identification of a time-space window for the compound events and cascading effects scenario assessment, and definition of risk/impact metrics;
2) identification of the triggering hazards affecting the case study regions;

3) identification of selected cascading effects scenarios which covers all possible interactive causal chains of events and interactions between relevant hazards;
4) probabilistic assessment of each compound event/cascading effects scenario, considering the occurrence of a triggering hazard with a certain magnitude;
5) exposure and vulnerability assessment for each cascading effects scenario, taking into account the dynamic vulnerability of risk receptors to the hazards (interactive causal chain) and including the influence of time, space, and human behaviour;
6) definition of resilience components (i.e., coping, adaptive, and transformative capacities) together with related metrics, and resilience assessment;
7) loss estimation and risk/impact assessment. This includes the cumulative damage on risk receptors following the sequence of events.

2.1.1. Compound events and cascading effects

Complex hazard events, whether natural or anthropogenic, may occur individually (i.e., single-hazard) or in various combinations (i.e., multi-hazard), and propagate differently in time and space. Consequently, the repercussions on socio-eco-technological systems may be more or less severe depending on the typology of the elements at risk (e.g., people, buildings, infrastructures, economy, etc.), the intrinsic characteristics of each typology, the spatial distribution of the elements and the mutual interdependencies among elements and between elements and the system to which they belong. Such complex events represent the highest manifestation of cumulated vulnerabilities at different scales (also tending to highlight the "unresolved vulnerabilities" of the community involved), including socio-technological and economic drivers (Pescaroli & Alexander, 2015; Pescaroli & Alexander, 2018).

In the context of the ICARIA project, "complex events" include the study of compound events and associated cascading effects. The two concepts are defined as follows:

- *Compound events* represent a specific category of extreme events due to their growing frequency and intensity. These 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, see Section 2.1.4) that drastically amplify their impact (IPCC, 2012). Compound events pertain to the natural environment and climate change domains and 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.

  Examples of compound events could be those that occurred with Hurricane Sandy (October 29, 2012) when the triggers were intensified by the climate change conditions. As a matter of fact, while the super-storm generated storm surges along the coast, the cold air from the Arctic intensified cold weather thus generating snow storms inland, concurrently (Kunz *et al.,* 2012; Blake *et al.,* 2013; Pescaroli & Alexander, 2016; Pescaroli & Alexander, 2018). In literature, compound events, are also referred to as "cascading events" (Zuccaro *et al.,* 2018; National Academies of Sciences, Engineering, and Medicine, 2022), whose effects increase in progression over time and generate unexpected secondary, tertiary, etc. events of strong impacts (Pescaroli & Alexander, 2015). This body of literature often encompasses under this definition the study of "interactive chains" (see Section 2.1.2), whether associated to a series of natural hazards, or a combination of natural and technological hazards (the so-called "NaTech hazards"). Within ICARIA project (see D2.1), the study of compound events is focused on i) the potential interrelations among climate change and natural hazards, and ii) the occurrence of non-correlated natural hazards, coincident or consecutive in time. The NaTech case – i.e., the propagation of impacts of compound events on exposed assets that generates technological hazard conditions originating from the failure of interconnected services and networks – is studied in ICARIA as part of the impact assessment (see D3.1) and linked to the concept of "cascading effects".

- *Cascading effects* can be considered as the dynamics of disasters whereby the impact of 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 services and assets (thus breaking sectoral silos and requiring a cross-sectoral analysis approach, see Russo *et al.,* 2020) and several repercussions on society and environment (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, 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).

  Continuing with the example of Hurricane Sandy, the presence in the affected area of critical assets and service networks originated a series of cascading effects, ranging from the leaks from refineries and chemical plants, sudden fires, interruption of public transportation, prolonged power outages and damage to the gasoline production/distribution chain that lead to a second declaration of emergency (Kunz *et al.,* 2012; Blake *et al.,* 2013; Pescaroli & Alexander, 2016; Pescaroli & Alexander, 2018).

  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 impact assessment framework (see D3.1).

2.1.2. Multi-hazard spatio-temporal relationships

As previously mentioned, complex events are characterised by a sequence of compound events and cascading effects that can affect multiple exposed assets and services. Consequently, their impacts can be much more severe than those of single hazards considered separately, both in terms of direct/indirect damage and geographical extension of the affected area, due to existing systemic interrelations between environmental, socioeconomic and technological systems. Therefore, assessing the overall impact/risk is the prerequisite for developing ad hoc resilient strategies and measures that also take into consideration the interdependencies between all sectors involved (Alexander, 2000; Kadri *et al., 2*014, Russo et al., 2020).

The ICARIA holistic modelling framework aims at highlighting the overall process logic required for multi-hazard risk/impact assessment in the case of compound events and related cascading effects. To this aim, it is designed to take into account the probability of occurrence of different possible event paths and assessing the cumulative damage on exposed assets (Zuccaro *et al.,* 2018). The modelling process, which supports the development of impact (and resilience) scenarios, depends on the availability of meteorological data, exposure data for different risk receptors categories (taking into account also interdependencies among assets and services considered), hazard models, and risk/impact models connected to specific hazard sources.

Before analysing the "elementary bricks" holistic modelling framework and their correlation, it is necessary to clarify that a sequence of multiple climate events can be visualised through a timeline comprised of 1) a single interactive causal chain, if a triggering event induces a single “event tree” (FIGURE 6a), or 2) a sequence of two or more interactive causal chain in parallel, if a triggering event induces more “event trees” in parallel (FIGURE 6b). In the second case, the timeline is made up of subsequent events not necessarily characterized by a cause-effect relationship.

The proposed modelling framework for compound events and cascading effects, whose main theoretical references pertain to the field of risk sciences and emergency management for geophysical events (Marzocchi *et al.,* 2009; Marzocchi *et al.,* 2012; Aubrecht *et al.,* 2012; Komendantova *et al.,* 2014; Garcia-Aristazabal *et al.,* 2015, Zuccaro et al., 2018), is based on a scenario analysis which consists of assessing damage induced to risk receptors by specific interactive causal chains represented as a timeline of events (time-history). Generally, the single timeline is chosen according to a series of specific criteria such as the probability of occurrence of the time-history and the overall repercussions on specific risk receptors, just to mention some examples.

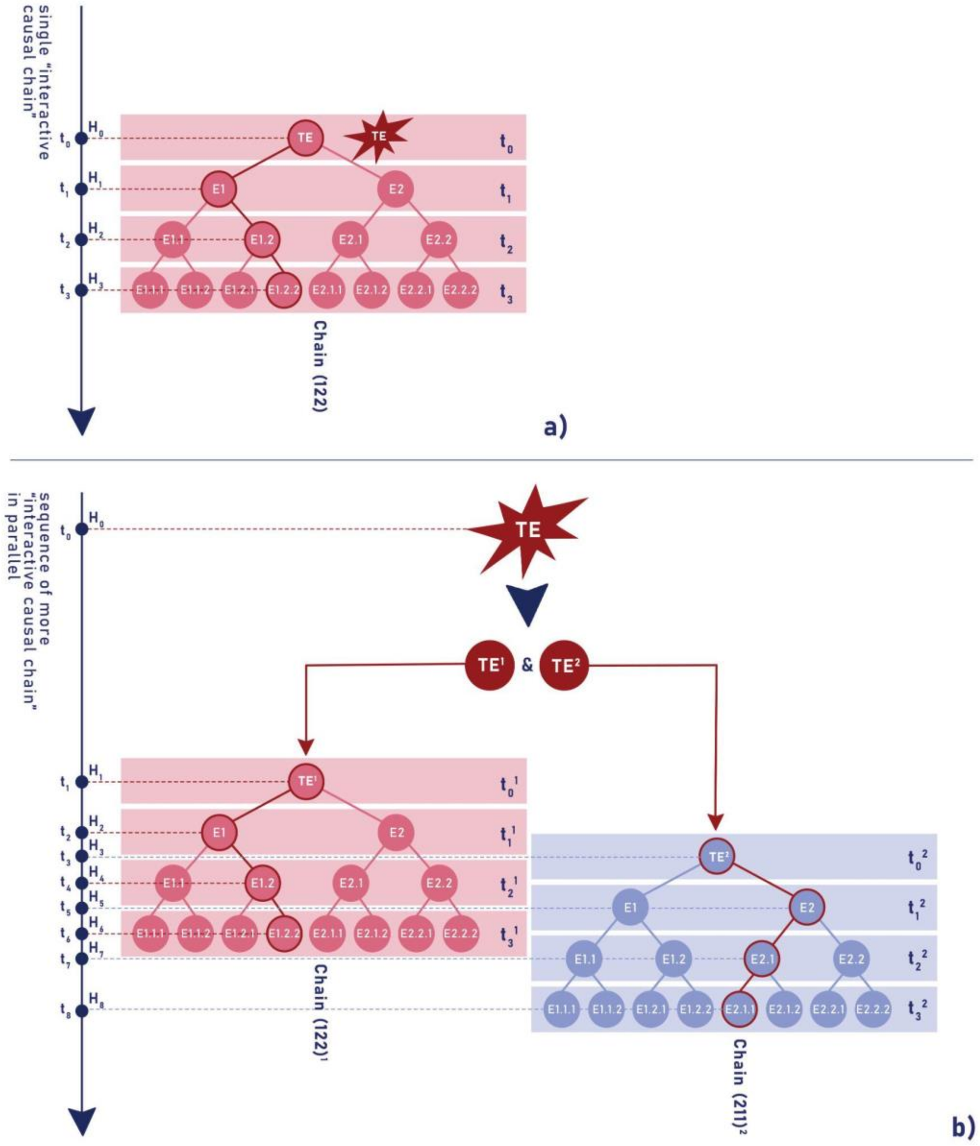


Figure 6. Timeline representation of a) a single interactive causal chain, or b) a sequence of more interactive causal chain in parallel (modified after Zuccaro *et al.,* 2018) where “TE” is Triggering Event, “E” is Event, and “t” is Time.

Mainly inspired by the procedure defined by Marzocchi *et al.* (2012) and consolidated through the EU-FP7 SNOWBALL project (Zuccaro *et al.,* 2018), an event-tree/time-history approach for the identification of compound/cascading conditions for each scenario analysis is incorporated in the ICARIA holistic modelling framework (see Section 2.1.3).

In this sense, a reliable and all-encompassing scenario – which includes the assessment of compound hazards and the cascading impact on assets – should be developed using 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 (FIGURE 8).

2.1.3. The elementary brick model

The ICARIA holistic modelling framework assumes "elementary bricks" as units of analysis (FIGURE 7, TABLE 1): *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.

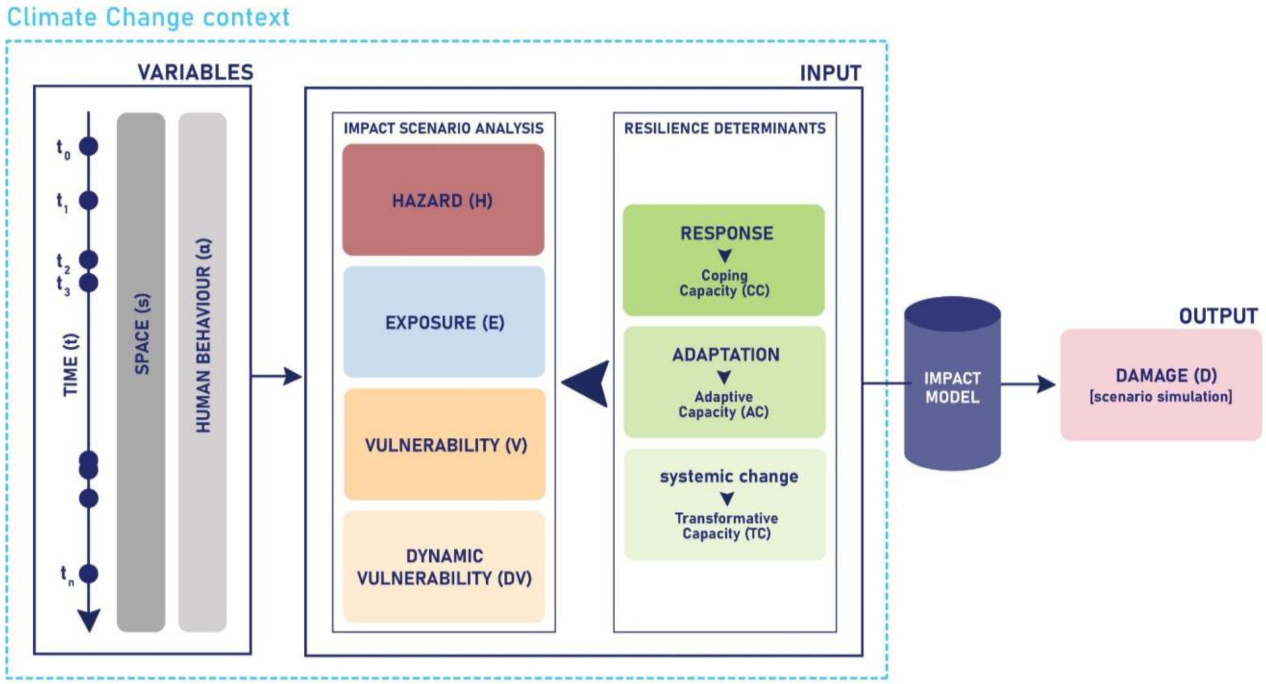


Figure 7. Holistic modelling framework for multi-hazard risk/impact/resilience assessment, covering combined events and their cascading effects. Main elementary bricks are represented (modified after Zuccaro *et al.,* 2018 and Russo *et al.,* 2023).

Both Time and Space represent the reference frame of the other elementary bricks. Hazard, initial Exposure, and initial Vulnerability represent the input data in "peacetime", while Dynamic Vulnerability manifests itself gradually, as a consequence of combined phenomena. Coping, Adaptive and Transformative Capacities represent those elementary bricks through which identifying actions that can improve resilience, considering combined phenomena. Damage on risk receptors is the output data of the risk/impact/resilience scenario assessment. Human behaviour, as an additional factor within the procedure, has the capacity to drastically influence the other elementary bricks (except time and space).

Table 1. Elementary bricks used in the ICARIA holistic modelling framework.

Elementary bricks	Description
TIME (t)	*TIME: Moment in which an event of given intensity occurs.* Multi-hazard risk/impact assessment, related to a sequence of multiple climate events, also requires the identification of a temporal reference frame. This frame coincides with the minimum temporal unit for analysing the model's input/output data. The time scale adopted in the model is represented by the single instants t_0, t_1, …, t_k, …, t_n, that characterize each hazard within the sequence. The sequence occurs from the triggering event (TE = H_0), at start time t_0, to the event n ($E_n = H_n$), at start time t_n. The interactive causal chain timeline of events reflects the time-history of cascading effects and everything that can influence them (e.g., human behaviour).
SPACE (s)	*SPACE: Geographical area in which an event of given intensity occurs.* Multi-hazard risk/impact assessment, related to a sequence of multiple climate events, requires the identification of a geographical reference frame. This frame coincides with the minimum space unit for analysing the model's input/output data.
HAZARD (H)	*HAZARD: Time-space distribution of the intensity of an event, characterized by an assigned probability of occurrence in a given time and space.* ICARIA holistic modelling framework is focused on a single interactive causal chain timeline of events (i.e., time-history of compound events and cascading effects), chosen in relation to the probability of occurrence of the time-history and repercussions on specific risk receptors. The probability of occurrence can be estimated through the analysis of past events together with the expert judgement and/or elicitation techniques. Within the framework, the hazard is defined by the time-space distribution of magnitude (M) of all hazards (H_0, …,H_1, …, H_k, …, H_n) in the chain: H_k [M(s)].
EXPOSURE (E)	*EXPOSURE: 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 specific moment (i.e., time).* The exposure analysis consists in grouping, at start time t_0, the elements belonging to the same exposure category and characterized by similar vulnerability (under the effect of each hazards H_k), in new categories called "vulnerability classes" ($VC_j^{e\,\|\,Hk}$): [$VC_j^{e\,\|\,Hk}$ (s)]$_{t0}$.
VULNERABILITY (V)	*VULNERABILITY: Distribution of the probability that one or more risk receptors of assigned characteristics are damaged by a given hazard intensity.* For each "vulnerability classes", the vulnerability can be assessed through *vulnerability curves* (Zuccaro et al., 2018) that represent the probability that a specific "vulnerability class" overcomes a certain level of damage D_i, due to a given hazard magnitude. Vulnerability functions are defined for each exposed element, under the effects of each single hazard H_k: V [P ($D \geq D_i \,\|\, E^e \cap H_k$)].
DYNAMIC VULNERABILITY (DV)	*DYNAMIC VULNERABILITY: "Procedure" that updates the vulnerability of one or more risk receptors, following a sequence of events of given intensities.*

	Sequences of multiple climate events progressively increase the vulnerability of exposed elements in relation to the damage evolution process. The implementation of a dynamic vulnerability model, borrowed from the EU-FP6 EXPLORIS project (EXPLORIS, 2002; Zuccaro *et al.,* 2008; Zuccaro & De Gregorio, 2013) and EU-FP7 CRISMA project (CRISMA, 2012; Garcia-Aristizabal *et al.,* 2014; Aubrecht *et al.,* 2013; Garcia-Aristizabal *et al.,* 2014), is based on a step-by-step updating of both exposure and vulnerability, taking into account how each event could increase the vulnerability compared to the previous event. The model assigns a vulnerability class proportionally to the level of damage, thus indicating the damage probability curves to be used when the next event occurs.
COPING CAPACITY (CC)	*COPING CAPACITY: strategies/measures that individuals, organizations and/or systems use to "cope with" abrupt adverse conditions, absorbing impacts and reacting ex-post (short-term response) through all available resources. The main purpose is restoring the state of well-being as it was before the crisis*.
ADAPTIVE CAPACITY (AC)	*ADAPTIVE CAPACITY: strategies/measures that individuals, organizations and/or systems use in advance to anticipate crisis, considering what happened in past events (long-term response). The main purpose is to bring incremental changes to guarantee future well-being*.
TRANSFORMATIVE CAPACITY (TC)	*TRANSFORMATIVE CAPACITY: capability/opportunity of individuals, organizations and/or systems to access assets/funds and be engaged in decision-making processes, with the aim of defining shared pathways for future crisis prevention and transformation of community functioning (long-term response). The main purpose is to bring incremental changes to guarantee and enhance future well-being, with a specific focus on GHG emissions reduction and SDGs achievement*.
DAMAGE (D)	*DAMAGE: Distribution of damage occurred on one or more risk receptors, expressed in the number of damaged elements for each damage class and/or monetary value of their restoration*. Providing the time-space distribution of damage to the exposed elements caused by an interactive causal chain timeline of events, it represents the output of the ICARIA holistic modelling framework: D_e (t,s). The damage scenario, resulting from the modelling procedure applied to the chain, takes into account i) the temporal distribution of the damage level for each element in all time steps of analysis, and ii) the spatial distribution of the damage level (e.g., n. of deaths, n. of collapsed buildings, sec./min./hours of power line interruption, etc.) for each element within exposure categories.
HUMAN BEHAVIOUR (α)	*HUMAN BEHAVIOUR: Influence factor of hazard, exposure, vulnerability, dynamic vulnerability, coping capacity, adaptive capacity, and transformative capacity.* In the time-space distribution of damage, human behaviour has to be taken into account as a factor able to influence cascades. This factor is directly linked to the reactive, adaptive, and transformative side of resilience (Reason, 1995; Provitolo, 2011; Barret *et al.,* 2012; Schmidt & Galea, 2013).

2.1.4. Time, space and human behaviour

The time and space factors are key aspects for climate risk/impact assessment, determining specific hazard conditions depending on the different climate projections, which help determine the expected trends and frequency/intensity of extreme events. Furthermore, the SSPs, introduced within AR6 (see also D1.2), associate GHG emission trends with high-level policymaking and climate action strategies, thus directly connecting the space and time variables to climate-resilient development implementation at the global and local scales. In these scenarios, differences in air pollution control and variations in climate change mitigation stringency strongly affect anthropogenic emissions trajectories (IPCC, 2021).

In particular, in relation to the assessment of impacts from complex events, the time factor has a key-role because repercussions of sequences of multiple climate-related events depend both on damage amplification and presence of subsidiary disasters over time (Pescaroli & Alexander, 2015). As a matter of fact, the temporal dimension influences the cumulative damage on risk receptors only when the timeframe needed to restore their functionality is shorter than the overall time needed to analyse the cascading effect scenario considered. Conversely, time is determinant in the evaluation of damage to critical infrastructures, grid, and/or service networks since the timeframe required for their restoration, albeit within certain limits, could be much shorter than the time of analysis, thus avoiding subsequent negative effects on people, assets, services, environment, etc.

Time must then be considered as a significant variable with regard to resilience measures covering the whole DRM cycle (UNISDR, 2015) in terms of *prevention* (e.g., construct sea-walls to protect settlements from storm surge, have alternative electricity sources in case of sudden disruption by floods or wind storms, etc.), *preparedness* (e.g., prepare and periodically update civil protection plans, develop training and exercises programmes for the Civil Protection system, inform and educate communities on local risks, etc.), *response* (e.g., firefighting, water pumping, provide medical assistance, provide protection measures/safe places for the population or evacuate it, provide temporary housing for evacuees, etc.), and *recovery/rehabilitation/reconstruction* (e.g., reconstruct damaged assets, restore services, etc.).

Resilience strategies and measures are designed to reduce the local factors aggravating the hazard magnitude, the exposure and the vulnerability of risk receptors in the short-, mid-, and long-term.

The “hazard”, “exposure/vulnerability” and “damage” elementary bricks are defined in function of their geographical distribution in space. This means that interactive causal chains of events can affect risk receptors at different scales (local, regional, national and/or international), thus causing damage whose severity and extent varies case-by-case. This is why a minimum spatial reference unit has to be adopted: the municipal area or even smaller for evaluations at the local level, the regional or the entire country for evaluations at the international/national level.

The spatial distribution of both hazards within the chain and exposed elements determines the type of damage induced by cascading effects. In this regard, there are two possibilities which are a) when a single element is affected by one hazard, whose damage is a function only of the vulnerability of the element affected by the single climate event, or b) when a single element is affected by two or more consecutive hazards, whose cumulative damage is a function of the progressive increase of the vulnerability of the element affected by a sequence of multiple climate events (depending on the evolution of the damaging process).

Behavioural aspects are also strictly connected with the time-history identified for the scenario analysis. Mid- to long-term trends of significant behavioural shifts at the community level are associated with the different SSPs, potentially impacting the resilience capacity of critical assets and services (e.g. energy and water uses, food habits and waste production/management). On the other hand, “reactive” behavioural aspects at individual/community and decision-making levels can depend on the specific time-history evolution, thus potentially impacting exposure and vulnerability conditions and the coping capacity (e.g. not following an evacuation order, diffusing alarming news, etc.), and ultimately the impact scenario. Consequently, “decision points” (Zuccaro *et al.,* 2018) can be included in the timeline of events together with hazards (FIGURE 8).

These aspects highlight the need of defining the timeline in accordance with requirements of decision makers and stakeholders, also considering the behavioural aspects that could exacerbate the impacts or even be triggering factors. In ICARIA, specific timeline(s) for the case study areas will be collaboratively built within the Communities of Practice.

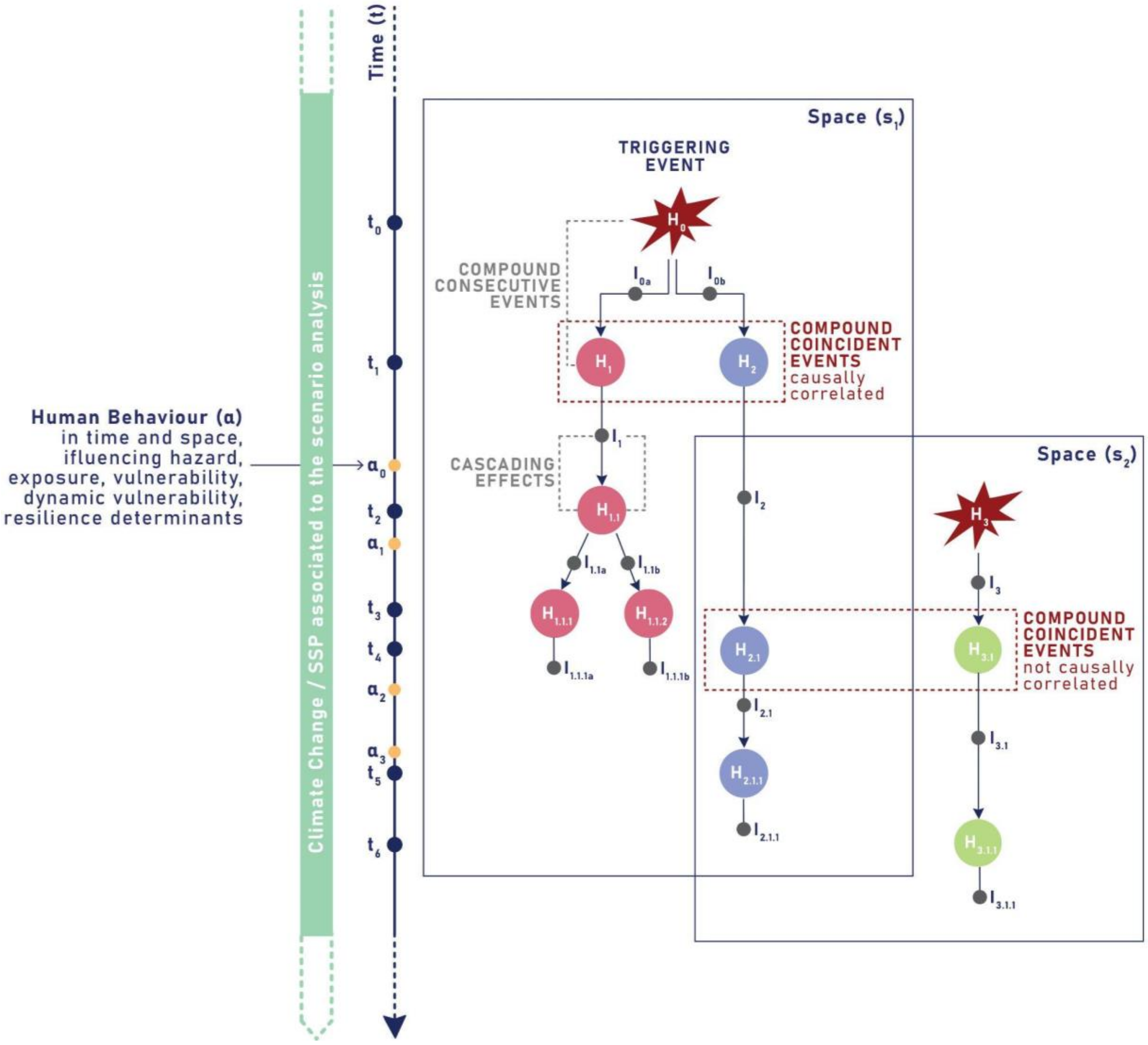


Figure 8. Timeline of events showing compound (coincident, causally or not causally correlated, and consecutive) events and cascading effects where "H" is Hazard, and "I" is Impact. The influence of key-variables (i.e., time, space, and human behaviour) in the risk/impact/resilience assessment process has been considered (modified after Zuccaro *et al.,* 2018).

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

According to the Sendai Framework (UNISDR, 2015), resilience can be defined as "the 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". Therefore, resilience to disruptive events involves not only the minimization of risks but also the ability to quickly return to the "normal" functioning. This is why the process of resilience analysis is based on the evaluation of how people, assets, services, environment, etc. (including their interdependencies) coexist in time and space, paying attention to their interconnected performance and capacities (Brugmann, 2012).

The emerging concept of "climate resilient development" (IPCC, 2023; Schipper *et al.*, 2022) is contributing to the evolution of resilience in the context of climate change, now expanded to achieve in an integrated way the mitigation, adaptation, and SDGs goals. This requires developing local coping, adaptive and transformative resilience strategies (see Section 2.2.1) according to short-, mid- and long-term climate projections and corresponding risk/impact assessments, so to support their planning and implementation in the local context, avoid the consequences resulting from mal-mitigation/mal-adaptation measures and take into account the associated social, economic and environmental co-benefits (Leone and Zuccaro*,* 2021).

Nowadays, resilience analysis is mainly addressed through a qualitative "vulnerability-oriented" (or "policy-oriented") approach, thus being quite far from the quantitative "risk-based" one, proposed by the IPCC AR5 (2014) and AR6 (2022), characterised by the centrality of hazard, exposure, and vulnerability as key-variables. Harmonising the two approaches involves identifying specific metrics associated with the complementary aspects (organisational, spatial, functional, physical) contributing to an overall evaluation of resilience that can be integrated into the risk/impact modelling workflow. These metrics should specifically allow to analyse the potential response to emergencies, the capacity of adaptation strategies and measures to prevent and reduce climate impacts, and the ability of complex socio-eco-technological systems to strengthen themselves through system-wide transformations (Russo *et al.,* 2023). However, within ICARIA, the resilience assessment goes beyond the variables that can be directly embedded in the modelling framework, to encompass a wider range of measures and metrics that contribute to the "scoring" of the overall resilience capacity at the local level based on the RAF App methodology and tools (see D3.2).

2.2.1. Resilience determinants

The ICARIA holistic modelling framework clearly shows how and why resilience could be incorporated within the multi-hazard risk/impact assessment process (FIGURE 5) through the characterization of Coping Capacity, Adaptive Capacity and Transformative Capacity. According to their peculiarities, CC, AC and TC resilience determinants can be distinguished as follows:

- *Coping Capacity* encompasses all strategies/measures employed by individuals, organizations, and/or systems to handle abrupt adverse conditions, enabling them to absorb impacts and respond retroactively. CC pertain mostly to organizations' and individuals' preparedness to respond and manifests itself in the short-term through all available resources in order to restore the state of well-being prior to the crisis (Birkmann *et al.,* 2009; Berman *et al.,* 2012; Keck & Sakdapolrak, 2013; IPCC, 2022). Therefore, appropriate and updated civil protection plans, (especially ones that are integrated and cover inter-sector response), information management systems that develop situational awareness, training and exercises, effective early warning systems, or financial resources available for acquiring essential goods during an emergency (e.g., food, medical assistance, temporary housing, etc.) represent some of the aspects that characterize the reactive side of resilience (Leone, 2020a; Leone 2020b; Turchi *et al.,* 2023).

- *Adaptive Capacity* concerns all strategies/measures employed by individuals, organizations, and/or systems in advance to anticipate future drastic changes (before they turn into disasters), based on past events. AC manifests itself gradually, in the long-term, through action/practices that bring incremental changes to guarantee the future well-being (Lemos & Tompkins, 2008; Birkmann *et al.,* 2009; Berman *et al.,* 2012; Keck & Sakdapolrak, 2013; IPCC, 2014; Wolfram, 2016; IPCC, 2022). Consequently, exploitation of research trajectories focused on climate risks or plans and programme for Disaster Risk Reduction (DRR) and Climate Change Adaptation (CCA) including site-specific adaptation actions represent some of the aspects that characterize the adaptive side of resilience (Leone, 2020a; Leone 2020b; Turchi *et al.,* 2023).

- *Transformative Capacity* pertains to individuals, organizations, and/or systems' ability and possibility to access assets/funds and participate in decision-making process, aiming at defining shared pathways for preventing future adverse conditions, and also radically transforming the functioning of communities involved. TC manifests itself gradually (as well as AC), in the long-term, enhancing future well-being (Berman *et al.,* 2012; Keck & Sakdapolrak, 2013; Wolfram, 2016). For example, strategic multi-stakeholder and civil society engagement or programs for emergency preparedness concern the transformative side of resilience since they may include operational tools (e.g., serious games, collaborative mapping, co-design processes, survey. interviews, training, etc.) which are in turn organized within the framework of participation. These tools represent a discriminant between AC and TC, because they activate bottom-up transformation processes by identifying community strengths and weaknesses - this means analysing risk perception, risk knowledge, predisposition to “live with” risk, etc. - shared priorities and needs, feasible solution (Raven *et al.,* 2018).

2.2.2. Resilience metrics

With the aim of shifting from a qualitative to a quantitative approach to resilience analysis, a set of representative and potentially quantifiable metrics have been identified for all capacities, starting from the RAF App (Cardoso *et al.,* 2020a, Lopes *et al.,* 2019) previously developed within the RESCCUE project (RESCCUE, 2016; Velasco *et al.,* 2018).

The RAF App is aimed at evaluating urban resilience to climate change focusing on the whole city and its infrastructures/services (i.e., water supply, wastewater, stormwater, waste, energy, and mobility), and taking into account socio-political aspects whenever important for improving the overall level of resilience. Based on an objective-driven diagnosis, the RAF App identifies four dimensions through which defining and achieving several resilience objectives: organisational (city governance), spatial (urban space and environment), functional (strategic services in the city), and physical (infrastructure of the services). Within each dimension, objectives are appraised through criteria that, in turn, can be quantified with specific metrics. Metrics are estimated using baseline values, thus providing indications about the overall urban resilience development level. In this sense, each metric may be relevant to recognising the city’s and/or infrastructure/service’s preparedness, response and recovery capabilities concerning one or more climate hazards (i.e., floods, combined sewer overflows, heat/cold waves, wind storms, or drought in both the most likely and most severe scenarios) and related impacts, including cascading effects. For this reason, while on one hand the metrics are structured in a generic way to be applicable to different type of hazards, on the other they can achieve a high level of specificity depending on the type of infrastructures/services considered (e.g., water service: n. of days pumping stations were out of service because of power supply interruptions caused by the last climate related event, with similar or harsher climate variables than the most probable scenario). The final assessment is given by the achievement of resilience objectives within organisational, spatial, functional, and physical dimensions, determined by the number of metrics for each criterion and taking into account all the types of infrastructures/services involved.

The interpretation and selection of the RAF App metrics through the lens of resilience determinants has been carried out according to two main criteria:

- the representativeness, considering the ICARIA objectives and sub-objectives;
- the correlation with resilience determinants of Coping Capacity, Adaptive Capacity, and Transformative Capacity.

Among the RAF App 700 metrics, 342 have been preliminarily identified. These metrics analysed considering their organizational, spatial, physical, or functional dimension together with risk receptors involved, have been categorized into those relating to the field of hazard/impact quantitative modelling (tot. 289) and those relating to the field of social sciences (tot. 53). A further selection, carried out through the expert judgement, has reduced the overall number of representative metrics to 258 (tot. 213 relating the field of hazard/impact quantitative modelling while tot. 42 relating the field of social sciences), including 3 new additional metrics which have been specifically created for ICARIA project, in order to cover those themes not previously covered by the RAF App within social sciences field (see D3.2). During the implementation phase - in ICARIA it is entrusted to WP3 - Impact evaluation and DSS - the overall number of metrics can be further expanded according to the complexity of the contexts analysed. This is possible thanks to the exportability of the whole holistic modelling framework beyond ICARIA CS regions. It should also be stated that a relevance degree is assigned to each metric, namely: *essential*, corresponding to all metrics required to integrate the resilience assessment of any city or service; *complementary*, additional metrics corresponding to a more detailed resilience assessment; *comprehensive*, additional metrics recommended whenever a more in-depth assessment is aimed, for a city or service with higher maturity in its resilience path. Accordingly, depending on the resilience maturity level, the city or service aiming to apply the RAF may select a given set of metrics, according to their relevance (Cardoso *et al.,* 2020b).

Particular attention has been given to the 45 metrics that provide specific information about the social dimension of resilience (42 coming from those already selected in RESCCUE and 3 new ones). These metrics can be grouped into two categories, representative of i) collective engagement and risk awareness, and ii) organizational emergency preparedness. Those included in the first category have been selected considering the need to investigate and understand the type of engagement as well as the level of awareness in multi-hazard contexts. Community engagement is facilitated across a communication triad based on community information, community consultation and community participation. Each element of the triad differs in the nature of communicative and behavioural interactivity, in the level of power sharing and decision-making, and in how active community members are in creating meanings and developing solutions to complex social problems. Resources allocated to inform individuals at risk are often limited, thus compromising the process of community engagement (including the development of related tools) and awareness building (Janse & Konijnendijk*,* 2007). Those included in the second category have been selected considering the need to evaluate city's response to disasters. Existing literature suggests that, even if disaster preparedness plays a key-role in reducing the effects of natural disasters on human health, its level is progressively decreasing (Zsidisin *et al.,* 2004). On this purpose, the United Nations International Strategy for Disaster Reduction defines emergency preparedness as knowledge, capabilities, and actions of governments, organizations, community groups, and individuals "to effectively anticipate, respond to, and recover from, the impacts of likely, imminent or current hazard events or conditions" (UNISDR, 2009). Preparedness efforts range from individual-level activities (e.g., first aid training) to household actions (e.g., stockpiling of equipment and supplies), from community efforts (e.g., training and field exercises) to governmental strategies (including early warning systems, emergency plans, and dissemination of essential information in case of emergency). Perceived risk, past disaster experiences, knowledge of how to prepare for disasters, as well as sociodemographic characteristics such as gender, age, education, and family significantly influence both individual and community risk awareness and emergency preparedness, thus including related behaviours (Kohn *et al.,* 2012).

Subsequently, each selected metric has been properly framed within the domain of one or more resilience determinants, thus allowing for further advancement compared to previous theorizations (Turchi *et al.,* 2023). Among ICARIA metrics, 176 have been linked to the CC (145 in the hazard/impact quantitative modelling field while 31 in the social sciences field), 244 to the AC (208 in the hazard/impact quantitative modelling field while 36 in the social sciences field), and 26 to TC (5 in the hazard/impact quantitative modelling field while 21 in the social sciences field) as shown in TABLE 2 and TABLE 3:

Table 2. Metrics related to the hazard/impact quantitative modelling field, divided according to CC, AC, and TC domains.

***HAZARD/IMPACT QUANTITATIVE MODELLING* FIELD**			
Metrics	**Domain**		
	Coping Capacity	**Adaptive Capacity**	**Transformative Capacity**
Organisational	-	4	1
Spatial	1	6	-
Functional	79	89	-
Physical	65	109	5
TOT.	**145**	**208**	**5**

Table 3. Metrics related to the social sciences modelling field, divided according to CC, AC, and TC domains.

***SOCIAL SCIENCES* FIELD**			
Metrics	**Domain**		
	Coping Capacity	**Adaptive Capacity**	**Transformative Capacity**
Organizational	11	21	21
Spatial	-	-	-
Functional	15	15	-
Physical	5	-	-
TOT.	**31**	**36**	**21**

TABLE 4 shows an extraction of metrics pertaining to the social sciences field, with some examples of significant metrics associated with CC (2 out of 6 metrics), AC (3 out of 6 metrics), and TC (5 out of 6 metrics) resilience determinants. The table also indicate the key-questions behind metrics and the values assigned to related answers. Several metrics have a binary response since they either exist or do not exist within the analysed case study, such as the existence of volunteers and civil society organizations with a key-role in emergency (e.g., support to the population through fundraising activities, collection of essential goods, etc.). However, other metrics, such as community engagement, could have variable response due to the fact that they bring into play factors such risk perception, knowledge background and access to information, people's ability to activate bottom-up processes, daily life needs, etc.

The metrics reported in TABLE 4 refer to the civil society and its ability to face and/or prepare to face one or more risks. These metrics cover different aspects of civil organisation and how to prepare for hazardous events such as the existence, dimension, and strength of formal and informal citizens' networks and/or different stakeholders' groups and their involvement in the early warning, planning and preparation procedures. As can be seen, in these cases, a higher value is assigned when the civic society is engaged both in the planning and response phases.

Within T3.2 (see D3.2), the methodological approach to connect – for this subset of metrics – the response value resulting from the RAF App with specific risk/impact assessment indicators evaluated through modelling and simulations will be presented.

Table 4. Examples of metrics related to the social sciences field, divided according to the CC, AC, and TC domains.

***SOCIAL SCIENCES* FIELD**							
Capacities	**N.**	**Metric/ Indicator**	**Question**	**Response value**			
				3	**2**	**1**	**0**
CC	43a	*Existence of civil society focal points for citizens*	Existence of volunteers and civil society organizations acting as focal points for citizens after an event, and regularly thereafter, to confirm safety issues, needs etc.	yes = 3	-	-	no = 0
TC	2	*Civil society links*	Are civil society organisations engaged?	yes = 3	The city works with NGOs or volunteers to some extent. Volunteer capacity below city needs = 2	The city DRR stakeholders have started to engage NGO organisations and/or volunteers = 1	no = 0

TC	356	*Water service climate change recovery planning*	Is there a strategy or process in place for post-event service recovery and reconstruction?	There is a strategy / process in place. It is robust and well-understood by relevant stakeholders = 3	There is a strategy / process in place. It is well-understood by relevant stakeholders but has known weaknesses = 2	Some plans / strategies exist but they are not comprehensive or joined up or understood by relevant stakeholders = 1	No known plans = 0
CC & TC	5	*Use of mobile and e-mail "systems of engagement" to enable citizens to receive and give updates before and after a disaster*	Use of mobile and social computing-enabled systems of engagement. All information before, during and after an event is supported by email, available on mobile devices, supported by alerts on social media, used to enable an in-bound citizen to government flow allowing crowd sourcing of data on events and issues	All these are used in the city = 3	Some use is made, but there are larger gaps in the information available by this means = 2	Only rudimentary use of systems of engagement but interest in expanding this = 1	No use of systems of engagement = 0
AC & TC	17a	*Multi-stakeholder collaboration*	Does the city have a formal stakeholder engagement programme (including the most socially vulnerable and at need populations)?	Yes, a formal stakeholder engagement programme exists involving all stakeholders = 3	Yes, it exists but is limited to some sectors and social groups, or the involvement is infrequent = 2	No, but there is a process done on a regular basis ensuring engagement of all stakeholders = 1	No stakeholder engagement programme, or too limited = 0

CC, AC & TC	7	*Training delivery*	Existence and reach (to all sectors) of training courses covering risk and resilience issues.	There are training courses covering risk, resilience and disaster response offered across all sectors of the city including government, business, NGO and community = 3	The city has a track record of delivering resilience training to some sectors, but other sectors lack training and engagement = 2	Some training modules are available. Coverage and content need to be significantly improved = 1	Little or no relevant training exists that is tailored for the city = 0

Other metrics, not included in Table 4, are related to the potential response of specific assets and services to extreme events (e.g., buildings and open spaces, natural areas, water supply, wastewater, stormwater, energy, mobility, and waste) following the implementation of specific resilience measures.

This subset of metrics is expected to be fully integrated in the holistic hazard/impact modelling framework, through the methodological approach presented in D3.2.

Since there are several variables that influence the relation between risk/impact assessment and resilience determinants, the quantitative characterization of CC, AC, and TC actions cannot be generalized but must be evaluated in relation to specific case studies, due to their influence on local hazards (including their interdependencies), exposure, and vulnerability.

3. Data collection and harmonization

3.1. Trial and Mini-trial modelling architecture

ICARIA project focuses on three case study regions with profound geographical, environmental, and socioeconomical differences which will provide very useful considerations and insights for the holistic modelling framework development in a multi-hazard risk/impact assessment perspective. The **Barcelona Metropolitan Area (AMB)** and the **Archipelago of South Aegean Region** are located in the coastal area of the Mediterranean Sea and are facing increasingly climate extremes (e.g., storm surges, pluvial floods, heatwaves, drought and forest fire) with huge impacts in socioeconomic and environmental terms. The third one, the **Salzburg Region,** is located in Austria and is particularly sensitive to the effects of climate change (e.g., glacier melt and heatwaves) that directly impact the prevailing energy production assets (extremely critical infrastructures) and other important sectors. Seven additional follower regions will be considered for potential replication beyond the project.

Across different climate-related hazard categories and their multiple interrelations (e.g., complex and compound disasters), case studies will be used to test the risk/impact modelling methodology and technical solutions primarily through **Trials.** Secondarily, both development and execution of Trials will be used to implement **Mini-trials** in order to replicate ICARIA outcomes within the project (FIGURE 9). The main scopes of Trials and Mini-trials consist of overcoming i) the lack of adequate asset-level models for climate-related risk/impact and adaptation options, ii) the lack of adequate decision support for a holistic multi-hazard resilience assessment and planning, and iii) the lack of decision support for optimising interactions between climate change, climate adaptation (strategies, measures, etc.) and society. Therefore, a specific architecture was designed for Trial and Mini-trial representing meteorological drivers, climate hazards, hazard interactions, risk receptors, and related impacts that will be taken into account in both multi-hazard risk/impact assessment cycles.

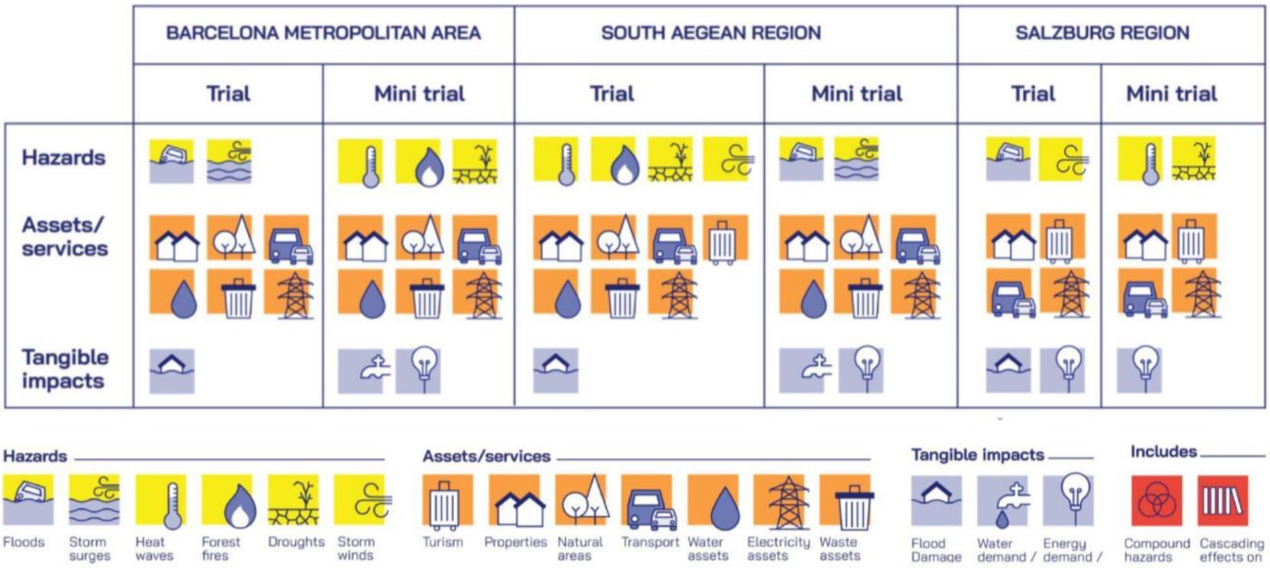


Figure 9. Simplified risk/impact assessment to be implemented (Trials) and replicated (Mini-trials) within each case study region.

3.1.1. ‘The Barcelona Metropolitan Area

The Barcelona Metropolitan Area (AMB) is the largest conurbation in Catalonia, consisting of 36 municipalities covering 636 square kilometres. With over 3.3 million inhabitants and a population density of 5188 people per square kilometre, it represents a geographical, social, demographic, economic and cultural space that has developed over the last century because of growth and connectivity between different urban systems around the city of Barcelona. It is the largest metropolitan agglomeration in the Western Mediterranean and is responsible for half (50.9%) of the GDP of Catalonia. In this context, there is a clear need to pay attention to climate risks in a region with an extraordinary population density, assets, strategic services, and critical infrastructure (AMB, 2023).

In 2016, following the outcome of the Paris Agreement, the authority of the AMB initiated the development of the Climate and Energy Plan 2030 (AMB, 2018). This plan acknowledges that the impacts of climate change in the region will continue to evolve throughout the 21st century and, for this reason, it is identified as one of the major threats and challenges for the entire region. According to the data from this plan, this climatic evolution will lead to higher temperatures (exceeding a 2°C temperature increase in the region by the end of the century). Specifically, from 1986 to the present, 10 heat waves have been recorded in the metropolitan area, with an extreme temperature event occurring every 4 years. The last 7 heat waves have occurred in the period from 2007 to 2022, increasing the frequency to one heatwave every 2 years. This is coupled with lower average annual precipitation and more intense and impactful extreme weather events. According to AMB 2018, among the various climate risks affecting the region, flash floods caused by extreme rain, sea level rise, extreme sea level (caused by storm surges) and heatwaves are among the primary risks for this region. These conclusions are aligned with numerous other reports and studies, including detailed projections provided by the RESCCUE project (RESCCUE, 2016; Russo *et al.* 2020) as outlined in the Barcelona Climate Plan (Ajuntament de Barcelona, 2018).

Furthermore, according to the Community of Practice (CoP) roadmap defined in Deliverable 5.4 of the ICARIA project (Turchi *et al.,* 2023b), the participant stakeholders were surveyed to understand their perception of risk about the different hazards that could affect the region. FIGURE 10 shows that on a scale from 0 to 10, floods (including pluvial floods, storm surges and sea level rise), droughts and heat waves were ranked as the most critical climate hazards for the AMB.

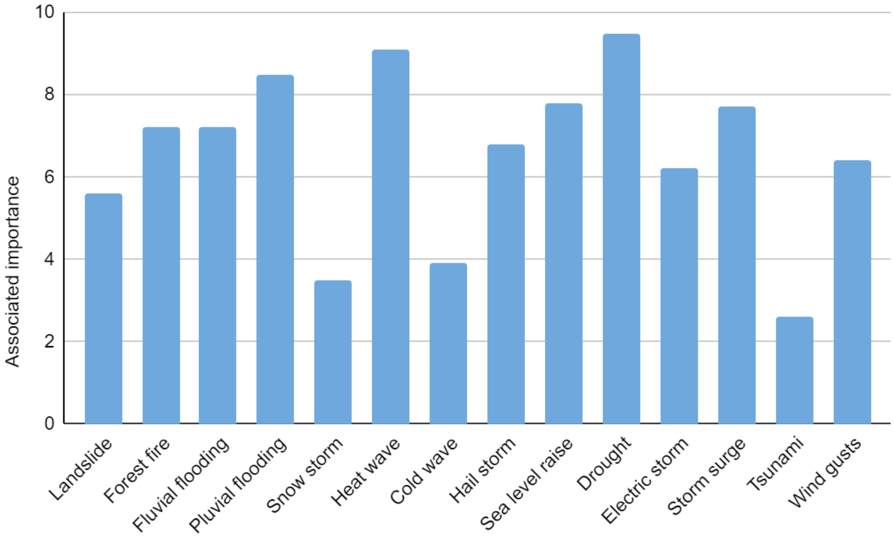


Figure 10. Results of the AMB CoP survey concerning the risk perception of different climate-related hazards by stakeholders involved.

Concerning multi-hazard risk/impact, the survey highlighted that the recent Storm Gloria, which occurred in January 2020, stressed the vulnerability of the region against compound events such as coincident storm surges and heavy rain. This event caused major damages in critical assets (e.g., infrastructures) and services across the region, with an estimated direct cost of more than 500M € (Sanuy *et al.,* 2021). Although the occurrence and impacts of such hazards have been addressed for some municipalities in the region, few studies have considered the impacts of events in which both hazards occur in combination (either simultaneously or consecutively). Events of this nature, as was clear during the Storm Gloria in 2020, result in significant economic, environmental, and human losses. In this context, the ICARIA project will analyse the occurrence and characteristics of historical combined extreme events in the AMB region, serving as a paradigm for the northwestern Mediterranean coastal area, and will assess the impacts related to future scenarios using different climate models and regionalized projections.

The initial CoP meeting also served to determine if the specific critical assets and services considered as risk receptors in the project proposal were coherent with the expectations and needs of the industrial partners of the working group. The electricity distribution network, water supply system, water sanitation, urban drainage infrastructure and transport network were some of the most relevant infrastructures to be considered in the case study framework.

As previously mentioned, a tailored case study architecture was designed both for the Trial and Mini-trial thanks to the expertise of ICARIA partners involved and the CoP survey.

On the one hand, the AMB Trial (FIGURE 11) will focus on flooding events caused either by extreme rain or extreme sea levels associated with storm surges. Also, a novel multi-hazard modelling approach will be developed to support risk/impact assessment of flooding events associated with a scenario of simultaneous occurrence of both hazards. On the other hand, the Mini-trials (FIGURE 12) will focus on the growing threat posed by persisting drought conditions, forest fires and heat wave conditions. Based on the intrinsic interconnection between these three hazards, their combined occurrence (coincident and consecutive) will be evaluated in the second risk/impact assessment cycle.

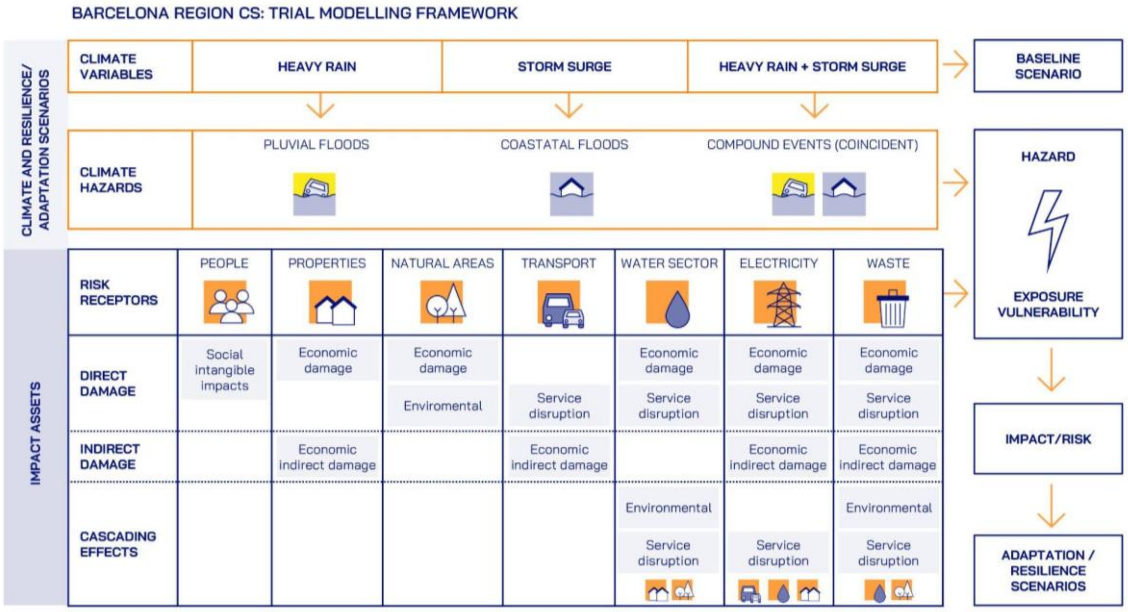
As it can be observed in FIGURE 11 and FIGURE 12, impacts on each receptor differ depending on the intrinsic characteristics of the receptor itself. The following bullet points depict main impacts that will be considered for the AMB:

- intangible damage to the "population" (e.g., mobility limitations), risk for pedestrians (Trial phase) or thermic discomfort (Mini-trial phase), will be assessed. Furthermore, human health repercussions and associated hospitalisation costs related to heat wave scenarios will be evaluated (Mini-trial phase);

- the "electricity distribution network", "water supply system", "water sanitation" and the "waste collection/management systems" are critical assets that provide primary services for individuals and communities. Therefore, their impact/risk assessment will involve two dimensions: i) direct damage to the exposed elements, in terms of both physical damage to singular infrastructures (e.g., wastewater treatment plants, electricity substations, water pumping stations, waste management facilities, etc.), and damage to the network system; ii) indirect damage caused by the service disruption. Due to the interconnected nature of urban systems, the service disruption of a primary service is likely to undermine other assets and services. In this regard, the economic repercussions of individual failures and cascading effects between interdependent services will be assessed too;

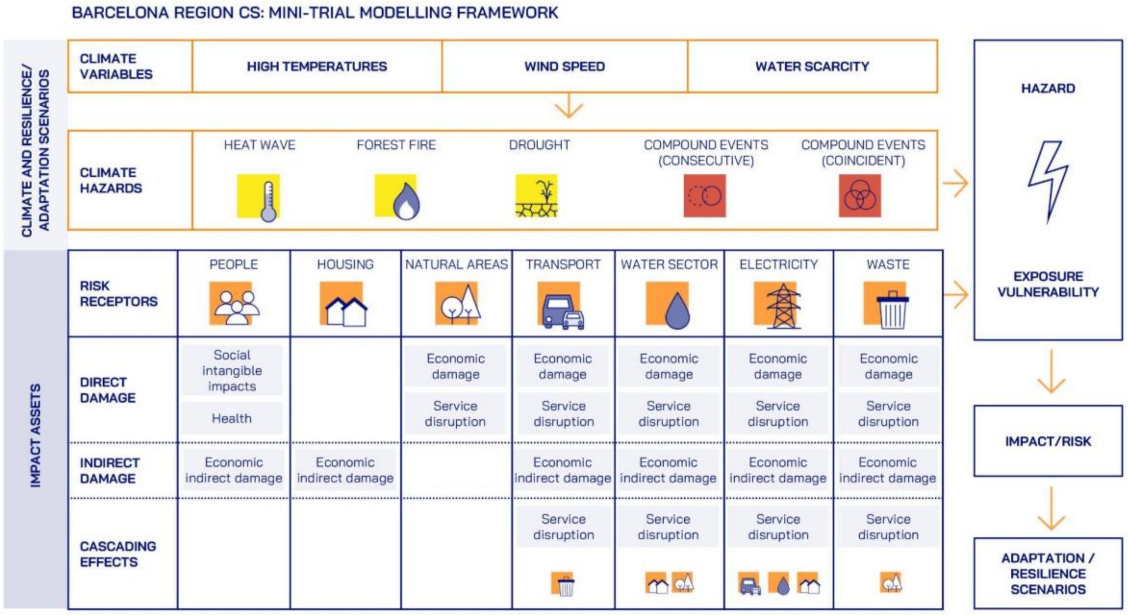
- similarly to the electricity distribution, water supply, and waste collection/management, direct/indirect damage and the economic repercussions will be quantified also for the "transport network";

- economic repercussions on "properties" (e.g., housing) and "natural areas" will also be addressed, being critical assets of interest for local communities and ecosystem services provision.



RISK RECEPTORS	PEOPLE	PROPERTIES	NATURAL AREAS	TRANSPORT	WATER SECTOR	ELECTRICITY	WASTE
DIRECT DAMAGE	Social intangible impacts	Economic damage	Economic damage Enviromental	Service disruption	Economic damage Service disruption	Economic damage Service disruption	Economic damage Service disruption
INDIRECT DAMAGE		Economic indirect damage		Economic indirect damage		Economic indirect damage	Economic indirect damage
CASCADING EFFECTS					Environmental Service disruption	Service disruption	Environmental Service disruption

Figure 11. TRIAL Modelling Framework architecture for Barcelona Region CS (produced by CETAQUA and AQUATEC).



RISK RECEPTORS	PEOPLE	HOUSING	NATURAL AREAS	TRANSPORT	WATER SECTOR	ELECTRICITY	WASTE
DIRECT DAMAGE	Social intangible impacts Health		Economic damage Service disruption	Economic damage Service disruption	Economic damage Service disruption	Economic damage Service disruption	Economic damage Service disruption
INDIRECT DAMAGE	Economic indirect damage	Economic indirect damage		Economic indirect damage	Economic indirect damage	Economic indirect damage	Economic indirect damage
CASCADING EFFECTS				Service disruption	Service disruption	Service disruption	Service disruption

Figure 12. MINI-TRIAL Modelling Framework architecture for Barcelona Region CS (produced by CETAQUA and AQUATEC).

3.1.2. The South Aegean Region

The South Aegean Region is an archipelago at the south-eastern edge of Greece that administratively includes the island clusters of the Cyclades and the Dodecanese. The Region has a total area of 5,286 square km and covers 4% of the total area of the country. With a population of 308,957 inhabitants (2.9% of total population) distributed across 52 inhabited islands, the GDP of the province accounts for 2.5% of the country's total GPD, mainly due to tourism and primary products. The effect of climate change in this region is more pronounced than in continental Greece or Europe and historical data, especially over the last 30 years, confirm it (increase of extreme weather events such as heavy rains, floods, forest fires, sea level rise, combined with heat waves of ever-increasing annual duration) (Katopodis *et al.* 2021; Politi *et al.* 2022; Politi *et al.* 2023).

Given the geographical distribution and geomorphology/geology of the entire South Aegean Region, emphasis was given to the most densely populated islands, Syros and Rhodes, chosen to implement the Trials. Indeed, both islands are affected by several meteorological extremes such as pluvial floods, heat waves, droughts, and wind storms whose effects could be further aggravated by forest fires in the summer. As reported by the CoP in the September 2023 meeting, the most critical climate hazards were extreme winds and drought/water scarcity for Syros island, while forest fires for Rhodes.
The second two most densely populated islands, Kos and Naxos, were chosen to replicate Mini-trials due to the fact that they represent ideal case studies for evaluating pluvial floods and landslide effects.

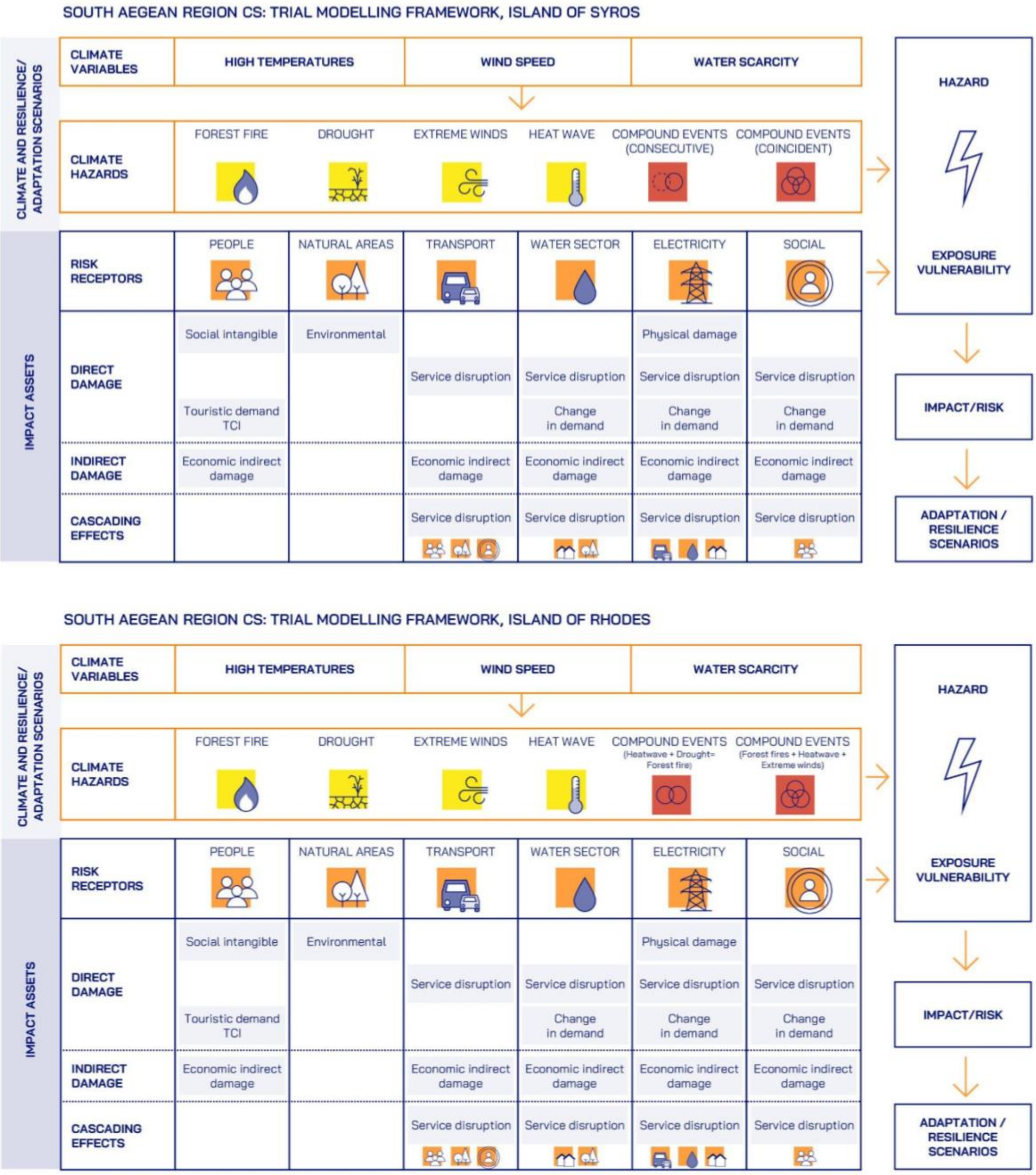
As done for all case studies, a case study specific architecture was designed both for the Trial and Mini-trial thanks to the expertise of ICARIA partners involved and the CoP survey.
Within the SAR Trials (FIGURE 13) the focus is mainly on urban flooding events (Syros), caused by both extreme precipitation and convective storms, and forest fires (Rhodes). Furthermore, the effects of heat waves, drought, and wind storms will also be analysed. Therefore, a novel multi-hazard modelling approach will be developed to support risk/impact assessment of these multiple events associated with a scenario of simultaneous occurrence of hazards. The Mini-trials (FIGURE 14) will focus on the growing threat posed by landslides and floods, on the islands of Kos and Naxos. Based on the intrinsic interconnection between these two hazards, their combined occurrence (coincident and consecutive) will be evaluated in the second risk/impact assessment cycle.

As it can be observed in FIGURE 13 and FIGURE 14, impacts on each receptor differ depending on the intrinsic characteristics of the receptor itself. The following bullet points depict the main impacts that will be considered for SAR:

- intangible damage to the "population" (e.g., mobility limitations), risk for pedestrians (Trial phase) will be assessed. Furthermore, human health repercussions and associated hospitalisation costs related to heat wave scenarios will be evaluated;

- the "electricity distribution network", "water supply system", and "water sanitation" are critical assets that provide primary services for individuals and communities. Therefore, their impact/risk assessment will involve two dimensions: i) direct damage to the exposed elements, in terms of both physical damage to singular infrastructures (e.g., wastewater treatment plants, electricity substations, water pumping stations, etc.), and damage to the network system; ii) indirect damage caused by the service disruption. Due to the interconnected nature of urban systems, the service disruption of a primary service is likely to undermine other assets and services. In this regard, the economic repercussions of individual failures and cascading effects between interdependent services will be assessed also in this case;

- the “transport network” is also a critical asset that provides a primary service for both individuals and communities. In the case of SAR, it consists of ports, airports, and roads. Similarly to the electricity distribution and water supply, direct/indirect damage and the economic repercussions will be quantified also for the “transport network”.



SOUTH AEGEAN REGION CS: TRIAL MODELLING FRAMEWORK, ISLAND OF SYROS

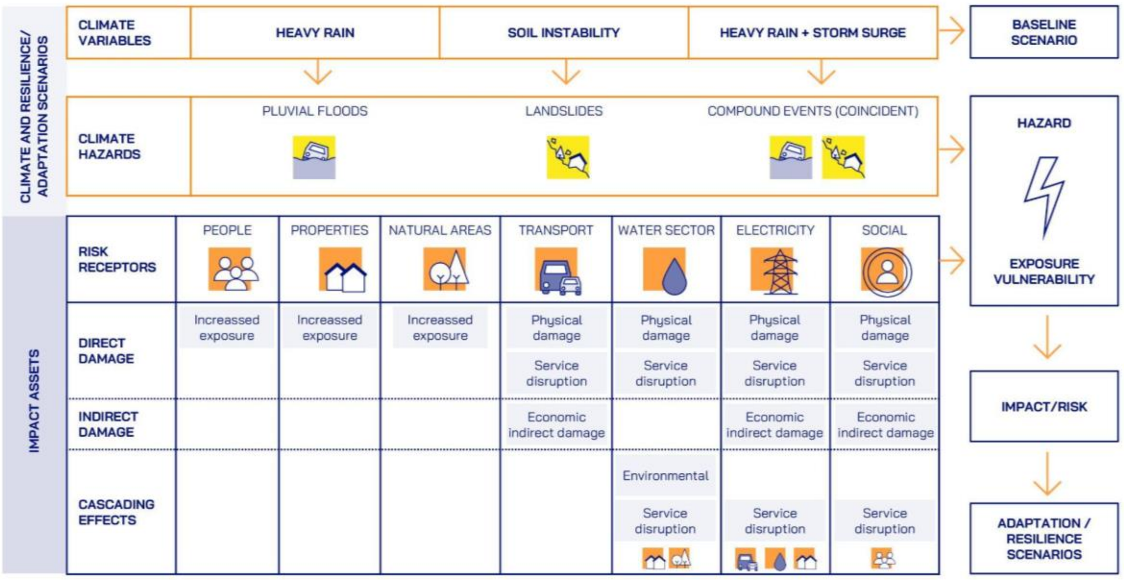
CLIMATE VARIABLES	HIGH TEMPERATURES		WIND SPEED		WATER SCARCITY	
CLIMATE HAZARDS	FOREST FIRE	DROUGHT	EXTREME WINDS	HEAT WAVE	COMPOUND EVENTS (CONSECUTIVE)	COMPOUND EVENTS (COINCIDENT)
RISK RECEPTORS	PEOPLE	NATURAL AREAS	TRANSPORT	WATER SECTOR	ELECTRICITY	SOCIAL
DIRECT DAMAGE	Social intangible Touristic demand TCI	Environmental	Service disruption	Service disruption Change in demand	Physical damage Service disruption Change in demand	Service disruption Change in demand
INDIRECT DAMAGE	Economic indirect damage		Economic indirect damage	Economic indirect damage	Economic indirect damage	Economic indirect damage
CASCADING EFFECTS			Service disruption	Service disruption	Service disruption	Service disruption

SOUTH AEGEAN REGION CS: TRIAL MODELLING FRAMEWORK, ISLAND OF RHODES

CLIMATE VARIABLES	HIGH TEMPERATURES		WIND SPEED		WATER SCARCITY	
CLIMATE HAZARDS	FOREST FIRE	DROUGHT	EXTREME WINDS	HEAT WAVE	COMPOUND EVENTS (Heatwave + Drought= Forest fire)	COMPOUND EVENTS (Forest fires + Heatwave + Extreme winds)
RISK RECEPTORS	PEOPLE	NATURAL AREAS	TRANSPORT	WATER SECTOR	ELECTRICITY	SOCIAL
DIRECT DAMAGE	Social intangible Touristic demand TCI	Environmental	Service disruption	Service disruption Change in demand	Physical damage Service disruption Change in demand	Service disruption Change in demand
INDIRECT DAMAGE	Economic indirect damage		Economic indirect damage	Economic indirect damage	Economic indirect damage	Economic indirect damage
CASCADING EFFECTS			Service disruption	Service disruption	Service disruption	Service disruption

Figure 13. TRIAL Modelling Framework architecture for South Aegean Region: a) Syros Island, and b) Rhodes Island (produced by CETAQUA and NCSRD/SAR).

SOUTH AEGEAN REGION CS: MINI-TRIAL MODELLING FRAMEWORK, ISLAND OF NAXOS



SOUTH AEGEAN REGION CS: MINI-TRIAL MODELLING FRAMEWORK, ISLAND OF KOS

Figure 14. MINI-TRIAL Modelling Framework architecture for South Aegean Region: a) Naxos Island, and b) Kos Island (produced by CETAQUA and NCSRD/SAR).

3.1.3. The Salzburg Region

Salzburg is situated in the Eastern Alps region of Austria. It is home to 562.704 inhabitants, covers 7.154,56 km² and represents one of the major tourist areas in the country. It consists of 5 provinces and its capital is the city of Salzburg. Since 1880, a significant increase (approx. 2°C) in the average air temperature has been recorded in Austria and the mountainous regions are already suffering from the effects of global warming such as rapid melting of glaciers, thawing of permafrost, increasing number of hot days, or changes in rain patterns towards extreme values. Climate change has increasing impacts on human beings, housing, infrastructures, services, environment, local economy, and energy production. Since the region plays an important role in energy production due to the available hydro power plants, the observed and projected changes in prevailing conditions (e.g., precipitation or storm events) cause higher risks to the availability of energy due to its impacts on both the hydro power plants themselves and the related energy network. Even though Austria is increasingly affected by climate change, the overall living conditions were and are mostly still favourable. Therefore, the urgency of understanding and quantifying current and future climate risks was only partly considered until after the Paris Agreement with one single study being done in 2012 that quantified the impact of climate change if only limited actions are performed to mitigate and adapt (Steininger *et al.,* 2016; PARATUS, 2022).
Mountainous regions are affected by increasing temperature and the related effects such as changed precipitation patterns, melting glaciers and unstable rock. The need to adapt to changing conditions was met by the Salzburg region in 2017 by establishing a climate adaptation concept, where the areas at risk (e.g., tourism, housing, etc.) and the climate hazards were identified. Further, possible adaptation measures were indicated. In 2022 a review of the adaptation concept was published, clearly stating the vulnerability of the region. Yet, the estimated impacts of climate change on the different sectors were purely based on expert opinion and only qualitatively assessed.

Within Salzburg, ICARIA project focuses on the Pinzgau geographical area as it was affected by multiple extreme events over the past years. Especially flooding events have impacted the energy, transport and housing sectors. A fact that was also highly present in the first CoP meeting, where the main hazards and impacts on critical assets were gathered. Most highly important hazards mentioned relate to precipitation events, as depicted in FIGURE 15.

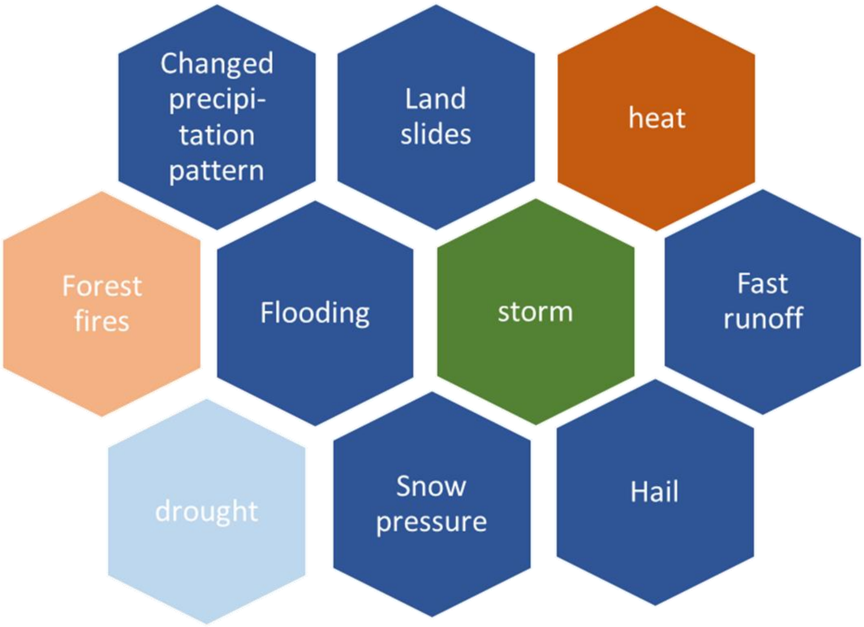


Figure 15. Identified hazards in CoP meeting, where the blue ones relate to precipitation.

Especially flooding events related to extreme precipitation have caused severe damage in the past, for instance July 2022 was first characterised by extreme high temperatures and ended with extreme thunderstorms, that formed in the unstable air masses and caused flooding of small streams, closing off small settlements and causing landslides that further intensified the damage. To protect the settlements from future flooding, a torrent barrier was installed. This barrier represents a technical adaptation solution, which, however, only works as long as it is not clogged by debris or trees. In general, the risk of flooding is extremely intensified over the whole region, with convective induced flooding becoming more prominent. The impact of compound or consecutive occurrence of storms and extreme precipitation has not been investigated so far in detail, even though it is of great importance for this region due to different reasons: i) storms and related uprooting of trees might clog the torrent barriers, thereby hindering them from effectively protecting settlements and infrastructure; ii) areas with dense forests tolerate higher critical level of accumulation than those with fewer forests.

Within the SBG case study, flooding related to precipitation is considered while related impacts such as landslides are explicitly excluded as we don’t have the expertise within the Consortium.

Within the CoP meeting, the energy infrastructure, prevailing settlements, and transport network were identified as being highly at risk in case of precipitations and wind-related events. Heat and drought, as well as wildfires, were characterised as emerging hazards. Therefore, stakeholders are aware but don’t feel the urge to adapt yet.

As done for all case studies, a tailored case study architecture was designed both for the Trial and Mini-trial thanks to the expertise of ICARIA partners involved and the CoP survey.

Within the SBG Trial (FIGURE 16) the focus is on flooding events caused either by extreme precipitation, on the one hand due to convective storms and on the other hand due to cyclones. Furthermore, the impact of storms and their change in future climate conditions will be assessed. As a novel multi-hazard modelling approach, a scenario of simultaneous occurrence of both hazards will be developed to support risk/impact assessment. The Mini-trials (FIGURE 17) will focus on the growing threat posed by persisting drought, heat waves and related risks of forest fires. Based on the intrinsic interconnection between these three hazards, their combined occurrence (coincident and consecutive) will be evaluated in the second risk/impact assessment cycle.

As it is displayed in FIGURE 16 and FIGURE 17, impacts on each receptor differ depending on the intrinsic characteristics of the receptor itself. The following bullet points depict the main impacts as identified within the CoP and that will be considered for the SBG case study region:

- intangible damage to the “population” (e.g., mobility limitations, Trial phase) or thermic discomfort (Mini-trial phase) will be assessed. Furthermore, human health repercussions and associated hospitalisation costs related to heat wave scenarios will be evaluated (Mini-trial phase);

- the “electricity distribution network” displays a critical asset that provides primary services for individuals and communities, beyond the considered region. Therefore, the impact/risk assessment will involve two dimensions: i) direct damage to the exposed elements, in terms of both physical damage to singular infrastructures (e.g., hydropower plants), and damage to the network system; ii) indirect damage caused by the service disruption;

- the “transport network” represents a bottleneck for the rural areas of Salzburg and damage to it can result in closed-off settlements with no means to get to or from these areas. Therefore, the damage due to physical damage as well as cascading effects will be assessed;

- economic repercussions on "properties" (e.g., housing) will also be addressed, as in the previous CS, being critical assets of interest for local communities and ecosystem services provision.

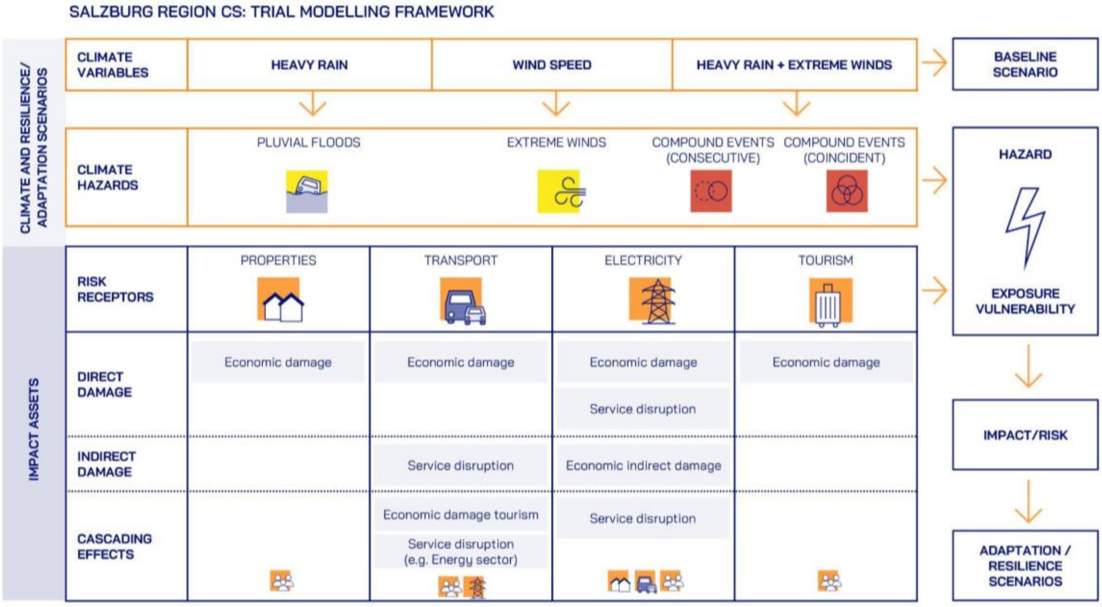


Figure 16. TRIAL Modelling Framework architecture for Salzburg Region (produced by CETAQUA and AIT).

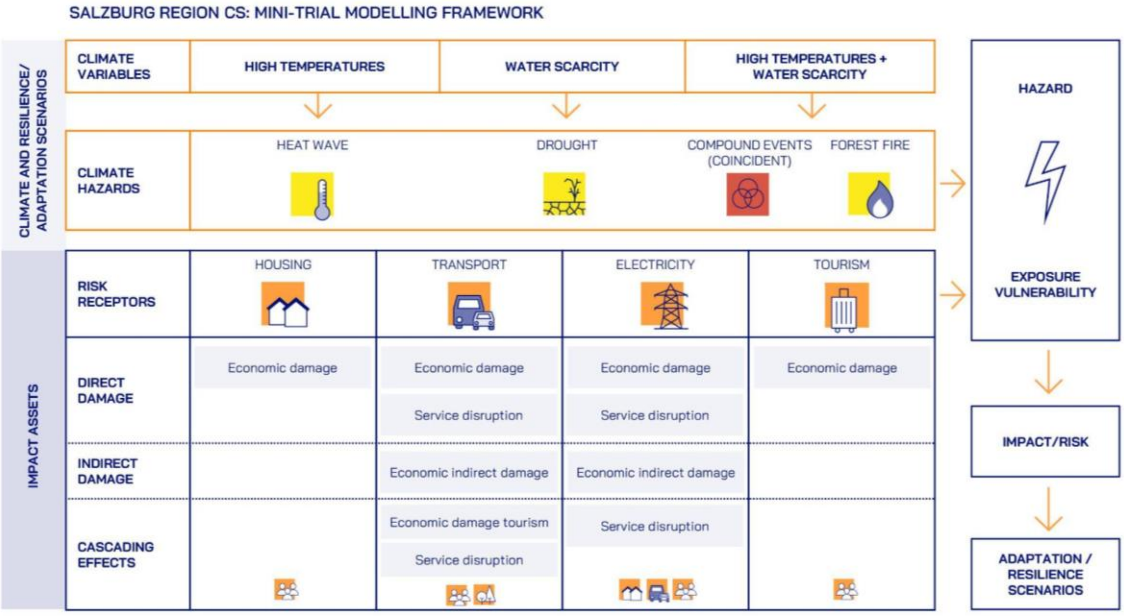


Figure 17. MINI-TRIAL Modelling Framework architecture for Salzburg Region (produced by CETAQUA and AIT).

3.2. Key-variables and datasets

Creating a consistent holistic modelling framework for multi-hazard risk/impact assessment across different climate-related hazards represents a complex challenge that becomes even more demanding when the modelling framework needs to be exportable beyond project case studies (see Sections 3.1.1, 3.1.2, and 3.1.3). A framework with these ambitions is easily prone to gaps and uncertainties throughout its development and implementation, according to several aspects that must be taken into account: i) climate-related hazards (including their interrelations) involved within each case study; ii) exposure/vulnerability related to hazards; iii) time and space variables; iv) scale of risk/impact analyses; v) usability of available databases.

ICARIA will use different approaches including artificial intelligence and already existing data-driven methodologies, borrowed from other EU H2020 projects such as CLARITY and RESCCUE (CLARITY, 2017; RESCCUE, 2016), to address data gaps and uncertainties. Therefore, a thorough classification of the state-of-the-art methodologies will serve as a useful scaffold for addressing relevant aspects such as hazard, exposure, vulnerability and impact of climate adaptation measures and related social, economic, and environmental co-benefits.

For this purpose, a comprehensive “cookbook” of methodologies (Task 1.3 - Modelling input requirements and methods to treat data gaps and uncertainties) will be compiled primarily focusing on addressing and bridging data gaps and uncertainties identified during the replication stage (Trials and Mini-trials), and several techniques based on automated and cost-effective downscaling, extrapolation or substitution with proxy data will be used. The process of gathering and harmonizing data becomes gradually challenging and ambiguous when advancing from a single to a multi-hazard risk/impact assessment modelling. Indeed, such challenges arise from the need to consider several hazard types, various exposure levels, and multiple levels of vulnerability across an array of dimensions, which might ultimately result in uncertainties in the accuracy, consistency, and comprehensiveness of available data. To keep the projected information updated, the “cookbook” development will follow a self-consistent approach, ensuring that data-driven methodologies to address data gaps and uncertainties are both continually updated and optimally categorized to fulfil the ICARIA Trials and Mini-trials specific requirements.

To ensure that Task 1.3 is aligned with the holistic modelling framework, an overview of datasets available and potentially usable in the implementation of Trials and Mini-trials has been carried out.

TABLES 5, TABLES 6, and TABLES 7, pertaining to the Trials, show the inputs and outputs datasets needed for the hazard, vulnerability and risk/impact assessment models, which can be used for the Metropolitan Area of Barcelona. The same tables have been also created for the South Aegean Region CS (TABLE 8, TABLE 9, TABLE 10, TABLE 11, TABLE 12, and TABLE 13) and Salzburg Region CS (TABLE 14, TABLE 15, and TABLE 16).

Table 5. Key input/output of the hazard assessment models for the Trial - Barcelona Metropolitan Area CS.

DATASETS	Climate Hazards					
	Pluvial floods		Coastal floods		Combined events	
	Kind of Data	Source	Kind of Data	Source	Kind of Data	Source
INPUT DATASETS						
Historic climatic variables	Historic pluvial data (highest time resolution possible).	EU/National/Regional meteorological agencies.	Historic sea level and wave height data (daily data).	Spanish ports authority.	Same data as for the previous two climatic hazards.	
	Rainfall of IDF curves at current time.	Task 1.2 output.	Sort surge IDF curves at current time.	Task 1.2 output.		
Future climate projections	Future IDF curves considering different CC scenarios and time horizons.	Task 1.2 output.	Future IDF curves considering different CC scenarios and time horizons.	Task 1.2 output.	Statistical return period of combined events.	Task 1.2 + 2.1 output.
	Return period for rainfall events of a given intensity and duration.	Task 1.2 output.	Return period events of a given intensity and duration.	Task 1.2 output.	Precipitation, runoff and return period of events.	Task 1.2 output.
	Digital Terrain Model (2x2m resolution).	ICGC.	Bathymetry of coastal area.	Regional DTM dataset.	Same data as for the previous two climatic hazards.	

Land use and terrain information	GIS information on urban buildings (building, dimensions, characteristics, kind of use).	GIS dataset.	GIS information on urban buildings (building, dimensions, characteristic, kind of use).	GIS dataset.	
	Complete sewer system network (pipes, connections, system overflows, pumping stations, etc.).	Local network operators.	-	-	
OUTPUT DATASETS					
Hazard Maps	Pluvial flooding maps showing flood depth and water velocity in the flooded areas for events of a given return period for the current scenario, BAU and different future CC projections.		Coastal flooding maps showing flood depth and water velocity in the flooded areas for events of a given return period for the current scenario, BAU and different future CC projections.		Flooding maps showing flood depth and water velocity in the flooded areas for combined events of a given return period for the current scenario, BAU and different future CC projections.

Table 6. Key input/output of the vulnerability assessment models for the Trials - Barcelona Metropolitan Area CS.

DATASETS	Climate Hazards					
	Pluvial floods		Coastal floods		Combined events	
	Kind of Data	Source	Kind of Data	Source	Kind of Data	Source
INPUT DATASETS						
Hazard maps	Pluvial flooding maps showing flood depth and water velocity in the flooded areas.	WP2 output.	Coastal flooding maps showing flood depth and water velocity in the flooded areas.	WP2 output.	Combined events flooding maps showing flood depth and water velocity in the flooded areas.	WP2 output.
Risk assessment on the critical asset: PEOPLE	Map of population distribution (density of inhabitants) (source: AQUA/CET). Population demographic characteristics (information per census district is the total inhabitants, people density, age and number of foreign people) (source: AQUA/CET). Social intangible impact curves (source: AQUA/CET).					
Risk assessment on the critical asset: PROPERTIES	Information about building typology (characteristics and location of entries to the building at street level to assess potential flood height inside properties) (source: CATASTRO ESPAÑA). Map of characteristics / typology of properties (kind of property according to its use: housing, commercial store, restaurant, public servic, etc.) (source: CATASTRO ESPAÑA). Damage curves on buildings (economic damage vs water height according to the kind of property) (source: RESCCUE project).					
Risk assessment on the critical asset: NATURAL AREAS	Location of natural assets of interest to assess the exposure to the hazards (source: AMB).					
Risk assessment on the critical asset: TRANSPORT	Map of urban and interurban bus services (source: Barcelona public transport company). Map of Barcelona Metro lines and services (source: Barcelona public transport company). Structural characteristics of Metro Stations (information about station entrances (e.g., entrance dimensions, location, anti-flooding measures, …) (source: Barcelona public transport company). Assets data and vulnerability curves specific for each transport service considered in the study (curves indicating “economic damage vs. water depth” and/or “% of operational failure vs water depth”) (source: results of ICARIA project).					

<table>
<tr><td>Risk assessment on the critical asset: WATER SECTOR</td><td colspan="3">Historic data on impacts and reparation cost on “interceptor de la costa” (revision of operational information to identify which events have impacted this infrastructure and the costs associated to its reparation).
Framework for WWTP classification of vulnerability to CC (source: results of ICARIAproject).
Assets data and vulnerability curves (curves indicating “economic damage vs. water depth” and/or “% of operational failure vs water depth”) (source: Results of ICARIA project).</td></tr>
<tr><td>Risk assessment on the critical asset: ELECTRICITY SECTOR</td><td colspan="3">Location of electricity distribution system critical assets (working with IREC on shortlisting the specific assets of the electricity distribution network that we will focus on) (source: IREC).
Assets data and vulnerability curves (curves indicating “economic damage vs. water depth” and/or “% of operational failure vs water depth”) (source: IREC).
Method to economic damage caused by failure of the electricity distribution system based on kind of business affected (this will focus on the cascading effects caused by electricity cuts, still working on that) (source: IREC/CET/AQUA/RESCCUE project).</td></tr>
<tr><td>Risk assessment on the critical asset: WASTE SECTOR</td><td colspan="3">Location of waste management system critical assets (with AMB we have shortlisted the main waste treatment facilities in the CS region) (source: AMB).
Assets data and vulnerability curves (curves indicating “economic damage vs. water depth” and/or “% of operational failure vs water depth”) (source: Results of ICARIA project).</td></tr>
<tr><td colspan="4">OUTPUT DATASETS</td></tr>
<tr><td>Vulnerability maps</td><td>Map representing the distribution of an asset/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability. These indicators are specific to each given asset and hazard.</td><td>Map representing the distribution of an asset/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability. These indicators are specific to each given asset and hazard.</td><td>Map representing the distribution of an asset/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability. These indicators are specific to each given asset and hazard.</td></tr>
</table>

Table 7. Key input/output of the risk/impact assessment models for the Trials - Barcelona Metropolitan Area CS.

DATASETS	Climate Hazards					
	Pluvial floods		Coastal floods		Combined events	
	Kind of Data	Source	Kind of Data	Source	Kind of Data	Source
INPUT DATASETS						
Hazard maps	Pluvial flooding maps showing flood depth and water velocity in the flooded areas.	WP2 output.	Coastal flooding maps showing flood depth and water velocity in the flooded areas.	WP2 output.	Combined events flooding maps showing flood depth and water velocity in the flooded areas.	WP2 output.
Vulnerability maps	Map representing the distribution of an assets/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability.	WP3 output.	Map representing the distribution of an assets/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability.	WP3 output.	Map representing the distribution of an assets/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability.	WP3 output.
OUTPUT DATASETS						
Risk maps	Risk maps showing which specific assets are affected by pluvial floods and the severity of this affection (e.g., % of asset failure, "High, medium, low"). Estimation of the economic damage associated with this affection (e.g., € of damaged equipment, € of reparation costs, € of economic loss due to business interruption).		Risk maps showing which specific assets are affected by coastal floods and the severity of this affection (e.g., % of asset failure, "High, medium, low"). Estimation of the economic damage associated with this affection (e.g., € of damaged equipment, € of reparation costs, € of economic loss due to business interruption).		Risk maps showing which specific assets are affected by combined event floods and the severity of this affection (e.g., % of asset failure, "High, medium, low"). Estimation of the economic damage associated with this affection (e.g., € of damaged equipment, € of reparation costs, € of economic loss due to business interruption).	

Table 8. Key input/output of the hazard assessment models for the Trial - South Aegean Region CS (part 1).

DATASETS	Climate Hazards					
	Heat waves		Extremes winds		Forest fires	
	Kind of Data	Source	Kind of Data	Source	Kind of Data	Source
INPUT DATASETS						
Historic climatic variables	Historic climate data (i.e., temperature, with highest time resolution possible).	HNMS.	Historic climate data (i.e., wind, with highest time resolution possible).	HNMS and ERA5.	FWI and EFFIS data.	Local fire services.
Future climate projections	Summer days, hot days, tropical nights, heat wave days, consecutive summer/hot days.	NCSRD.	Extreme winds data.	NCSRD.	FWI data.	NCSRD.
Land cover/use information	Urban land cover/use information and data.	Corine Land Cover.	Urban land cover/use information and data.	Corine Land Cover.	Urban land cover/use Information and data.	Corine Land Cover.
OUTPUT DATASETS						
Hazard Maps	Maps of summer days, hot days, tropical nights, heat wave days, consecutive summer/hot days of SAR demo sites.		High wind speed maps of SAR demo sites, frequency of occurrence.		FWI maps of SAR demo sites.	

Table 9. Key input/output of the hazard assessment models for the Trial - South Aegean Region CS (part 2).

DATASETS	Climate Hazards					
	Droughts		Floods		Combined events	
	Kind of Data	Source	Kind of Data	Source	Kind of Data	Source
INPUT DATASETS						
Historic climatic variables	Historic climate data (i.e., drought, with highest time resolution possible).	HNMS and JRC.	Historic rainfall and flood data (daily data/ flooded areas).	HNMS and Environment Ministry.	Same data as for the previous two climatic hazards.	
Future climate projections	Future projections for temperature, rainfall, SPEI, and SPI.	NCSRD.	Return period event of a given intensity and duration.	NCSRD.	IDF and return period of events.	NCSRD.
Land cover/use information	Digital Elevation Model (highest resolution possible).	ICGC.	Bathymetry of coastal area.	Regional dataset.	Same data as for the previous two climatic hazards.	
	GIS information on urban buildings and infrastructures.	OSM and NCSRD.	GIS information on urban buildings and infrastructures	OSM and NCSRD.		
	Urban land cover/use information and data.	Corine Land Cover.	Urban land cover/use information and data.	Corine Land Cover.		
OUTPUT DATASETS						
Hazard Maps	SPI and SPEI maps.		Pluvial flooding maps showing flooded areas based on return period events.		Maps with probability of compound events.	

Table 10. Key input/output of the vulnerability assessment models for the Trials - South Aegean Region CS (part 1).

DATASETS	Climate Hazards					
	Heat waves		Extreme winds		Forest fires	
	Kind of Data	Source	Kind of Data	Source	Kind of Data	Source
INPUT DATASETS						
Hazard maps	Maps of summer days, hot days, tropical nights, heat wave days, consecutive summer/hot days of SAR demo sires.	WP2 output.	High wind speed maps of SAR demo sites, frequency of occurrence.	WP2 output.	FWI maps of SAR demo sites.	WP2 output.
Risk assessment on the critical asset: PEOPLE	Maps of population per city/village (source: 2011 or 2021 CENSUS).					
Risk assessment on the critical asset: PROPERTIES	Maps of buildings (source: local database).					
Risk assessment on the critical asset: NATURAL AREAS	Location of natural areas assets of interest to assess the exposure to the hazards (source: SAR/NCSRD).					
Risk assessment on the critical asset: TRANSPORT	Maps of roads (source: SAR/OSM). Map of urban and interurban bus services (source: OSM). Map of ports and airports (source: NCSRD).					
Risk assessment on the critical asset: WATER SECTOR	Map of water distribution network (source: DEYA Syros/Syros Trial). Map of water reserves (source: SAR/Rhodes Trial).					

Risk assessment on the critical asset: ELECTRICITY SECTOR	Location of electricity distribution system critical assets (working with EXETER on shortlisting the specific assets of the electricity distribution network that we will focus on) (source: NCSRD).		
OUTPUT DATASETS			
Vulnerability maps	Map representing the distribution of an asset/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability. These indicators are specific to each given asset and hazard of this affection (e.g. % of asset failure, “High, medium, low”).	Map representing the distribution of an asset/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability. These indicators are specific to each given asset and hazard, tourists’ arrival reduction, € of economic loss due to business interruption).	Map representing the distribution of an asset/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability. These indicators are specific to each given asset and hazard.

Table 11. Key input/output of the vulnerability assessment models for the Trials - South Aegean Region CS (part 2).

DATASETS	Climate Hazards					
	Droughts		Floods		Combined events	
	Kind of Data	Source	Kind of Data	Source	Kind of Data	Source
INPUT DATASETS						
Hazard maps	Maps of summer days, hot days, tropical nights, heat wave days, consecutive summer/hot days of SAR demo sires.	WP2 output.	High wind speed maps of SAR demo sites, frequency of occurrence.	WP2 output.	FWI maps of SAR demo sites.	WP2 output.
Risk assessment on the critical asset: PEOPLE	Maps of population per city/village (source: 2011 or 2021 CENSUS).					
Risk assessment on the critical asset: PROPERTIES	Maps of buildings (source: local database).					
Risk assessment on the critical asset: NATURAL AREAS	Location of natural areas assets of interest to assess the exposure to the hazards (source: SAR/NCSRD).					
Risk assessment on the critical asset: TRANSPORT	Maps of roads (source: SAR/OSM). Map of urban and interurban bus services (source: OSM). Map of ports and airports (source: NCSRD).					
Risk assessment on the critical asset: WATER SECTOR	Map of water distribution network (source: DEYA Syros/Syros Trial). Map of water reserves (source: SAR / Rhodes Trial).					

Risk assessment on the critical asset: ELECTRICITY SECTOR	Location of electricity distribution system critical assets (working with EXETER on shortlisting the specific assets of the electricity distribution network that we will focus on) (source: NCSRD).		
OUTPUT DATASETS			
Vulnerability maps	Map representing the distribution of an asset/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability. These indicators are specific to each given asset and hazard of this affection (e.g., % of asset failure, "High, medium, low").	Map representing the distribution of an asset/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability. These indicators are specific to each given asset and hazard, tourists' arrival reduction, € of economic loss due to business interruption).	Map representing the distribution of an asset/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability. These indicators are specific to each given asset and hazard.

Table 12. Key input/output of the risk/impact assessment models for the Trials - South Aegean Region CS (part 1).

DATASETS	**Climate Hazards**					
	Heat waves		**Extreme winds**		**Forest fires**	
	Kind of Data	**Source**	**Kind of Data**	**Source**	**Kind of Data**	**Source**
INPUT DATASETS						
Hazard maps	Maps of summer days, hot days, tropical nights, heat wave days, consecutive summer/hot days of SAR demo	WP2 output.	High wind speed maps of SAR demo sites, frequency of occurrence.	WP2 output.	FWI maps.	WP2 output.
Vulnerability maps	Map representing the distribution of an assets/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability.	WP3 output.	Map representing the distribution of an assets/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability.	WP3 output.	Map representing the distribution of an assets/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability.	WP3 output.
OUTPUT DATASETS						
Risk maps	Risk maps showing which specific assets are affected by heat waves and the severity of this affection (e.g., % of asset failure, “High, medium, low”). Estimation of the economic damage associated with this affection (e.g., € of damaged equipment, € of reparation costs, € of economic loss due to business interruption).		Risk maps showing which specific assets are affected by extreme winds and the severity of this affection (e.g., % of asset failure, “High, medium, low”). Estimation of the economic damage associated with this affection (e.g., € of damaged equipment, € of reparation costs, € of economic loss due to business interruption).		Risk maps showing which specific assets are affected by combined event forest fires and the severity of this affection (e.g., % of asset failure, “High, medium, low”). Estimation of the economic damage associated with this affection (e.g., € of damaged equipment, € of reparation costs, € of economic loss due to business interruption).	

Table 13. Key input/output of the risk/impact assessment models for the Trials - South Aegean Region CS (part 2).

DATASETS	Climate Hazards					
	Drought		Floods		Combined events	
	Kind of Data	Source	Kind of Data	Source	Kind of Data	Source
INPUT DATASETS						
Hazard maps	SPI and SPEI maps.	WP2 output.	Coastal flooding maps showing flood depth and water velocity in the flooded areas.	WP2 output.	Likelihood of compounds.	WP2 output.
Vulnerability maps	Map representing the distribution of an assets/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability.	WP3 output.	Map representing the distribution of an assets/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability.	WP3 output.	Map representing the distribution of an assets/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability.	WP3 output.
OUTPUT DATASETS						
Risk maps	Risk maps showing which specific assets are affected by pluvial floods and the severity of this affection (e.g., % of asset failure, “High, medium, low”). Estimation of the economic damage associated with this affection (e.g., € of damaged equipment, € of reparation costs, € of economic loss due to business interruption).		Risk maps showing which specific assets are affected by coastal floods and the severity of this affection (e.g., % of asset failure, “High, medium, low”). Estimation of the economic damage associated with this affection (e.g., € of damaged equipment, € of reparation costs, € of economic loss due to business interruption).		Risk maps showing which specific assets are affected by combined events and the severity of this affection (e.g., % of asset failure, “High, medium, low”). Estimation of the economic damage associated with this affection (e.g., € of damaged equipment, € of reparation costs, € of economic loss due to business interruption).	

Table 14. Key input/output of the hazard assessment models for the Trial - Salzburg Region CS.

DATASETS	Climate Hazards					
	Fluvial floods		Wind storms		Combined events	
	Kind of Data	Source	Kind of Data	Source	Kind of Data	Source
INPUT DATASETS						
Historic climatic variables	Historic fluvial data (highest time resolution possible).	EU/National/Regional meteorological agencies.	Historic wind and gust data.	EU/National/Regional meteorological agencies.	Same data as for the previous two climatic hazards.	
	Precipitation and runoff.	Task 1.2 output.	-	-		
Future climate projections	Future precipitation events based on CC projections.	Task 1.2 output.	Future wind storm events based on CC projections.	Task 1.2 output.	Statistical return period of combined events.	Task 1.2 output.
	Return period for rainfall events of a given intensity and duration.	Task 1.2 output.	Return period events of a given intensity and duration.	Task 1.2 output.	Precipitation, runoff and return period of events.	Task 1.2 output.
Land use and terrain information	Digital Terrain Model (1x1m resolution).	SAGis (Salzburg database).	Digital Terrain Model (1x1m resolution).	SAGis (Salzburg database).	Same data as for the previous two climatic hazards.	
	Information on critical assets.	GIS dataset.	Information on critical assets.	GIS dataset.		
OUTPUT DATASETS						

Hazard Maps	Pluvial flooding maps showing flood depth and extent of covered areas, for a specific weather pattern of a given return period for the current scenario, BAU and different future CC projections.	Wind storm maps showing wind velocities for a specific weather pattern of a given return period for the current scenario, BAU and different future CC projections.	Maps for combined events of a given return period for the current scenario, BAU and different future CC projections.

Table 15. Key input/output of the vulnerability assessment models for the Trials - Salzburg Region CS.

DATASETS	Climate Hazards					
	Fluvial floods		Wind storms		Combined events	
	Kind of Data	Source	Kind of Data	Source	Kind of Data	Source
INPUT DATASETS						
Hazard maps	Fluvial flooding maps showing flood depth and in the flooded areas.	WP2 output.	Wind storm maps showing velocities in the affected areas.	WP2 output.	Combined events flooding maps showing flood depth and wind storm velocity in the flooded areas.	WP2 output.
Risk assessment on the critical asset: PROPERTIES	Information about building morphology (characteristics and location of entries to the building at street level to assess potential flood height inside properties) (source: RESCCUE). Damage curves on buildings (economic damage vs water height according to the kind of property) (source: Huzinga *et al.,* 2017, RESCCUE project).					
Risk assessment on the critical asset: TRANSPORT	Map of street network, damage reports related to past flooding / storm events (ASFINAG, OSM data). past damage related to extreme events that hit the street connecting the hydro power plant (VERBUND).					
Risk assessment on the critical asset: ELECTRICITY SECTOR	Location of electricity distribution system critical assets (working with VERBUND and IREC on shortlisting the specific assets of the electricity distribution network that we will focus on) (source: VERBUND, IREC). Assets data and vulnerability curves (curves indicating “economic damage vs. water depth” and/or “% of operational failure vs water depth”) (source: VERBUND). Method to economic damage caused by failure of the electricity distribution system based on kind of business affected (this will focus on the cascading effects caused by electricity cuts, still working on that) (source: IREC/VERBUND/RESCCUE project).					
OUTPUT DATASETS						

Vulnerability maps	Map representing the distribution of an asset/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability. These indicators are specific to each given asset and hazard.	Map representing the distribution of an asset/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability. These indicators are specific to each given asset and hazard.	Map representing the distribution of an asset/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability. These indicators are specific to each given asset and hazard.

Table 16. Key input/output of the risk/impact assessment models for the Trials - Salzburg Region CS.

DATASETS	Climate Hazards					
	Fluvial floods		Wind storms		Combined events	
	Kind of Data	Source	Kind of Data	Source	Kind of Data	Source
INPUT DATASETS						
Hazard maps	Fluvial flooding maps showing flood depth and water velocity in the flooded areas.	WP2 output.	Wind storm maps showing velocities in the affected areas.	WP2 output.	Combined events flooding maps showing flood depth and wind velocity in the affected areas.	WP2 output.
Vulnerability maps	Map representing the distribution of an assets/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability.	WP3 output.	Map representing the distribution of an assets/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability.	WP3 output.	Map representing the distribution of an assets/risk receptor vulnerability index derived from a set of indicators assumed to represent vulnerability.	WP3 output.
OUTPUT DATASETS						
Risk maps	Risk maps showing which specific assets are affected by fluvial floods and the severity of this affection (e.g., % of asset failure, “High, medium, low”). Estimation of the economic damage associated with this affection (e.g., € of damaged equipment, € of reparation costs, € of economic loss due to business interruption).		Risk maps showing which specific assets are affected by wind storms and the severity of this affection (e.g. % of asset failure, “High, medium, low”). Estimation of the economic damage associated with this affection (e.g., € of damaged equipment, € of reparation costs, € of economic loss due to business interruption).		Risk maps showing which specific assets are affected by combined event floods and storms and the severity of this affection (e.g., % of asset failure, “High, medium, low”). Estimation of the economic damage associated with this affection (e.g., € of damaged equipment, € of reparation costs, € of economic loss due to business interruption).	

Conclusions

The ICARIA holistic modelling framework (D1.1) provides a harmonized and consistent methodology to support the impact/risk/resilience assessment across different climate-related hazard categories from a multi-hazard risk point of view (covering complex interactions, such as compound events, and cascading effects), also providing for resilience analysis integration. It tries to ensure that both data and algorithms used to assess local hazards and related effects on risk receptors are responsive to any transformations carried out on the most critical assets, such as infrastructures and crucial services concerning water, transport, energy, waste, natural areas, or tourism sectors. In this sense, starting from the evaluation of possible direct and indirect damage, the methodology enables the correlation between suitable, sustainable, and cost-effective resilience strategies/measures and potential risk reduction benefits (social, environmental and economic),
The methodology behind the framework, which is service-oriented, tries to optimize the exploitation of satellite/remote sensing data and methods in order to address possible gaps and/or uncertainties. For this reason, it has been designed taking into account the impacts of strategies/measures on local hazards, exposure and vulnerability, and also the post-processing of modelling results through the cost-based and multi-criteria analysis as key-aspects of ICARIA DSS.

The Barcelona Metropolitan Area, South Aegean Region, and Salzburg Region, exposed to several combined climate-related hazards whose impacts could be further aggravated by the ongoing climate change and socioeconomic challenges, represent ideal CSs for testing technical and organisational solutions developed through ICARIA Trials and Mini-trials. However, the holistic modelling framework has the overarching ambition of being exportable and replicable beyond the three regions considered.

As the main reference document supporting the entire ICARIA project and determining its developments across WPs and Tasks, the D1.1 has been structured according to the following points:

- contextualization of the ICARIA holistic modelling framework;
- explanation of the reasons behind the development of a comprehensive and harmonized modelling framework for assessing risks/impacts from a multi-hazard perspective, as a consequence of combined climate events (complex interactions, characterised by compound events and cascading effects);
- clarification of taxonomies behind the framework;
- characterization of Hazard, Exposure, Vulnerability, Dynamic Vulnerability, Damage, Coping Capacity, Adaptive Capacity, and Transformative Capacity, time and space variables, and human behaviour variable as "elementary bricks";
- identification of CC, AC, and TC metrics in order to integrate resilience within risk/impact assessment process;
- overview of the CSs in terms of geographical location, climate-related hazards and most relevant events occurred, risk receptors, and expected direct and indirect damage;
- description of the correlation between the theoretical ICARIA holistic modelling framework and the Trial and Mini-trial implementation within each CS;
- identification of modelling gaps and uncertainties, paying attention to the data collection phase.

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 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 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 introduces 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 represent 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 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 as 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 assumes 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 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, 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 benefit (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 costs of an investment (e.g., adaptation/mitigation measure) by units of effectiveness. The number of lives saved is an example of unit of effectiveness for risk adaptation/mitigation measure (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 the 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 to 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 a “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 trend, drying trend, extreme temperature, extreme precipitation, precipitation, snow cover, damaging cyclone, sea level, ocean acidification, and carbon dioxide fertilisation. Non-climatic drivers include land use change, migration, population and demographic change, 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 enables 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 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, the exposure estimation also involves the 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 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, governments at different level. 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 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 actually occurred past events or as a result of 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 that is given when one service or infrastructure (donor) fails and makes fail another one (the receptor) (RESCCUE, 2016).

Losses: Amount of realized damages as 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.
More in general, it consists in 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 from 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 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 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 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 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 an 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). 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 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 the 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 element 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

. **Table 1.1.** Data used in preparation of ICARIA Deliverable 1.1

Dataset name	Format	Size	Owner and re-use conditions	Potential Utility within and outside ICARIA	Unique ID
-	-	-	-	-	-

Table 1.2. Data produced in preparation of ICARIA Deliverable 1.1

Dataset name	Format	Size	Owner and re-use conditions	Potential Utility within and outside ICARIA	Unique ID
-	-	-	-	-	-

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