

# D4.3 Replicability recommendations

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## D4.3 Replicability recommendations

### Summary

Deliverable 4.3 – “Replicability recommendation” presents the final stage of validation of the ICARIA project, focusing on the transferability and replicability of its asset-level modelling framework, methods and tools beyond the original Case Studies (CS): Barcelona Metropolitan Area (AMB), Salzburg Region (SLZ), and South Aegean Region (SAR). Building on previous validation of scientific robustness, the analysis adopts an application-oriented perspective through the implementation of Mini-trials – streamlined and lightweight configurations of the Trial Guidance Methodology (TGM), designed to assess how ICARIA solutions can be adapted to new geographical, hazard, risk/impact, and governance contexts under varying data and resource conditions. In most cases, Mini-trials build upon existing Trial architectures adapted for transferability and replicability purposes; in others, they are implemented as stand-alone simplified assessments. Across both pathways, the evaluation of potential socio-economic impacts associated with the application of ICARIA solutions and recommendations represents a consistent transversal objective. The assessment combines expert-based insights on technical feasibility, data requirements, costs, and implementation effort with stakeholder feedback on usability, usefulness, and adoption potential. Results indicate that ICARIA solutions are flexible and adaptable, but their replication is not automatic and depends on key enabling conditions, including data availability, modelling complexity, and institutional capacities. Stakeholders recognise their value for supporting risk-informed planning and adaptation, while highlighting the importance of usability, clarity of outputs, and integration with existing practices. Overall, the deliverable identifies both opportunities and constraints for scaling ICARIA solutions, providing evidence-based insights to support their application in broader contexts.

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## List of Acronyms and Abbreviations

AMB	Barcelona Metropolitan Area
AR6	Sixth Assessment Report
CC	Climate Change
CN	Curve Number
CoP	Community of Practice
CS	Case Study
CSF	Case Study Facilitators
DEM	Digital Elevation Model
DoA	Description of Action
DSS	Decision Support System
FWI	Fire Weather Index
GDP	Gross Domestic Product
HEC-HMS	Hydrologic Engineering Centre - Hydrologic Modelling System
IPCC	Intergovernmental Panel on Climate Change
KPI	Key Performance Indicator
MEMI	Munich Energy Balance Model for Individuals
PET	Physiological Equivalent Temperature
PV	Present Value
R50	50-year return period
RAF	Resilience Assessment Framework
RAT	Resilience Assessment Tool
RQ	Research Question

SAR	South Aegean Region
SDI-12	12-month Streamflow Drought Index
SLZ	Salzburg Region
SMA	Soil Moisture Accounting
SMART	Specific, Measurable, Achievable/Attainable, Relevant/Reasonable, Time-bound.
SOLWEIG	SOlar and LongWave Environmental Irradiance Geometry
SOTA	State Of The Art
SSO	Strategic Subobjective
SSP	Shared Socioeconomic Pathway
TGM	Trial Guidance Methodology
Tmrt	Mean Radiant Temperature
UHI	Urban Heat Island
UTCI	Universal Thermal Comfort Index
WP	Work Package
WRF	Weather Research and Forecasting
WWTP	Wastewater Treatment Plant

## Executive summary

This document, Deliverable 4.3 – “Replicability recommendations”, represents the **final stage of validation of the ICARIA project**, focusing on how its asset-level modelling framework, methods and tools can be applied beyond the original implementation settings. Building on the validation of scientific robustness achieved in previous activities, this document adopts a more **application-oriented perspective, addressing the conditions under which they can be effectively transferred, adapted, and replicated.**

This assessment is structured around the **implementation of Mini-trials**, which build upon the experience gained in the project Trials while adopting a more targeted and flexible approach. Mini-trials are conceived as streamlined and lightweight implementations of the Trial Guidance Methodology (TGM), designed according to two distinct approaches: **derived Mini-trials**, built upon existing Trial architectures and operationalised through the DSS, and **stand-alone Mini-trials**, implemented as independent simplified assessments entailing an explicit knowledge and approach transfer across Case Studies (CSs). Across both approaches, the evaluation of **socio-economic impacts associated with the application of ICARIA solutions and recommendations** constitutes a shared analytical priority, contributing to a more comprehensive understanding of their real-world value.

Within this context, a key distinction is made between transferability and replicability. **Transferability refers to the ability to apply ICARIA solutions across the existing CSs**, by testing them on different hazard and risk/impact scenarios and modelling configurations within the same region. **Replicability, in contrast, concerns the potential to implement the ICARIA approach in entirely new geographical, hazard, risk/impact, and governance contexts beyond the project**, where conditions, data availability, and user needs may differ significantly. By applying the ICARIA framework to new hazard and risk/impact configurations within each CS, Mini-trials enable the assessment of transferability under controlled yet diverse conditions, reducing complexity where needed. At the same time, they generate evidence on the requirements, constraints, and enabling factors that would influence replication in external contexts, including technical, organisational, and economic aspects.

A central feature of the analysis is the **integration of technical and user-oriented perspectives**. On the one hand, **expert-based insights** are used to examine the feasibility of transferring/replicating modelling workflows, highlighting key factors such as data requirements, methodological constraints, resource needs, and implementation timelines. On the other hand, **stakeholder feedback** captures perceptions of usefulness, usability, credibility, and added value, offering a realistic view of the conditions under which ICARIA solutions could be adopted and sustained in practice. This combined approach allows for a comprehensive evaluation that goes beyond technical performance to include real-world applicability.

The results indicate that the **ICARIA solutions are sufficiently flexible and can be adapted to different territories, even when data availability or modelling capacity is limited**. At the same time, **replicability depends on a set of enabling conditions**, including access to suitable data, the

level of simplification of modelling workflows, the clarity and interpretability of outputs, and the degree of support provided by integrated tools such as the Decision Support System (DSS). In this regard, **derived Mini-trials demonstrate that the DSS can serve as a key enabling factor for structured and resource-efficient transferability**, while stand-alone Mini-trials evidence that replicability in contexts without a prior Trial framework requires considerably greater effort. In this sense, replicability is not a direct extension of transferability but requires additional adaptation efforts and supporting measures.

Furthermore, the analysis highlights the **importance of socio-economic and organisational factors** in shaping the adoption potential of ICARIA solutions. Stakeholders recognise the value of ICARIA solutions in supporting risk-informed planning and adaptation strategies, but their willingness to adopt them is influenced by considerations such as cost, required expertise, integration with existing practices, and long-term sustainability.

Overall, Deliverable 4.3 demonstrates that **ICARIA offers a solid and adaptable basis for advancing climate risk/impact and resilience assessment** across different contexts. At the same time, it identifies **key areas for improvement** to enhance both transferability and replicability, including the need for clearer guidance, streamlined workflows, improved tool integration, and stronger alignment with user needs. The **lessons learned and recommendations** derived from the Mini-trials contribute to positioning the ICARIA project as a practical reference for supporting climate-resilient decision-making across different European contexts and beyond.

## 1. Introduction to Project ICARIA

The number of climate-related disasters has been progressively increasing over 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 occurred worldwide, causing 2.97 trillion US\$ losses and affecting 4 billion people (UNDRR, 2020). These numbers represent a sharp increase in the number of recorded disaster events in comparison with the previous twenty years. Much of this increase is due to a significant rise in the number of climate-related disasters (heatwaves, droughts, flooding, etc.), including compound events, whose frequency is dramatically increasing because of the effects of climate change and the related global warming. In the future, by mid-century, the world stands to lose around 10% of total economic value from climate change if the temperature increase stays on the current trajectory, and both the Paris Agreement and 2050 net-zero emissions targets are not met.

In this framework, **Project ICARIA** has the overall objective to promote the definition and the use of a comprehensive asset-level modelling framework to achieve a better understanding about climate-related impacts produced by complex, compound and cascading disasters and the possible risk reduction provided by suitable, sustainable and cost-effective adaptation solutions.

This project will be especially devoted to critical assets and infrastructures that are susceptible to climate change, in the sense that local effects can result in significant increases in the cost of potential losses for unplanned outages and failures, as well as maintenance, unless an effort is undertaken to make these assets more resilient. ICARIA aims to understand how future climate might affect life-cycle costs of these assets in the coming decades and to ensure that, where possible, investments in terms of adaptation measures are made up front to face these changes.

To achieve this aim, ICARIA has identified 7 Strategic Subobjectives (SSO), each one related to one or several Work Packages (WPs). They have been classified according to different categories: scientific, corresponding to research activities for advances beyond the state of the art (SSO1, SSO2, SSO3, SSO4, SSO5); technological, suggesting and/or developing novel solutions, integrating state-of-the art and digital advances (SSO6); societal, contributing to improved dialogue, awareness, cooperation and community engagement as highlighted by the European Climate Pact (SSO7); and related to dissemination and exploitation, aimed at sharing ICARIA results to a broader audience and number of regions and communities to maximize project impact (SSO7). The specifications for each SSO are provided below:

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

- SS04 – Increase the knowledge on climate-related disasters (including interactions between compound events and cascading effects) by developing and implementing advanced modelling for multi-hazard assessment;
- SS05 – Better assessment of holistic resilience and climate-related impacts for current and future scenarios;
- SS06 – Better decision-making for cost-efficient adaptation solutions by developing a Decision Support System (DSS) to compare adaptation solutions;
- SS07 – Ensure the use and impact of the ICARIA outputs.

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## 2. Objectives of the deliverable

**Deliverable 4.3 – “Replicability recommendations”** reports the outcomes of Task 4.3 – “Replication and Demos”. As defined in the Description of Action (DoA), this task builds upon and integrates output and results generated across multiple WPs: WP1, which provides the methodological foundation for the development of the asset-level modelling framework for risk/impact assessment, as well as climate change projections; WP2, focused on single- and multi-hazard assessment; WP3, addressing impact quantification, resilience assessment, and the development of DSS tools; and WP4 itself, in particular the design, implementation and evaluation of Trials within the project Case Studies (CS).

Deliverable 4.3 is structured around two main objectives:

- **assessing the transferability of the results** achieved in Task 4.2 – “Trial Implementation and Assessment” across the ICARIA CSs through the implementation of Mini-trials;
- **validating and consolidating these results through replication** in different geographical, hazard, risk/impact, and governance contexts (building on transferability assessed across the CSs).

In addition, Task 4.3 contributes to the broader validation and outreach of project results through **demonstration activities**, aimed at engaging stakeholders beyond the ICARIA CSs and exploring their interest in follow-up and replication initiatives. In this sense, Task 4.3 represents a shift from the comprehensive validation of ICARIA methods and tools carried out in previous tasks towards a more application-oriented evaluation of their usability, scalability, and relevance beyond the original project settings.

Tasks 4.2 and 4.3 are closely interconnected within the Trial Guidance Methodology (TGM) (Fonio et al., 2020; 2023) framework, as introduced in Deliverable 4.1 – “Trial Design” (Havlik et al., 2024), and follow a common methodological backbone articulated across two complementary streams of work. In Task 4.2, these streams are implemented through the full Trial activities, combining the testing and validation of the ICARIA resilience assessment tools and DSS with the development of extreme event risk/impact assessment (including cascading effects) for critical assets and services. These activities, presented in Deliverable D4.2 – “Trial Assessment” (de la Cruz Coronas et al., 2026), are structured according to the Trial architectures and event-tree scenarios already defined in Deliverable 1.1 – “ICARIA Holistic Modelling Framework” (Turchi et al., 2023a; Leone et al., 2025) and further refined in Deliverable 1.5 – “Implementation of ICARIA Holistic Modelling Framework - Lessons Learnt” (Leone et al., 2026). In this context, the same modelling logic is applied under simplified and adaptation-oriented configurations – either by **adapting existing Trial architectures for transferability and replicability purposes**, or through **stand-alone simplified assessments** where no prior Trial framework is directly transferable. In both cases, assessing the socio-economic implications of applying ICARIA solutions and recommendations constitutes a shared and overarching priority across all Mini-trial activities.

Considering the objectives outlined above, the structure of Deliverable 4.3 reflects both its methodological and application-oriented components. *Sections 1* and *2* provide an introduction to the

ICARIA project and define the objectives of the deliverable, respectively, setting the context for the subsequent analysis. *Section 3* presents the methodological framework underpinning the transition from Trials to Mini-trials. It first introduces the TGM and then describes the scope, objectives, and design of the ICARIA Mini-trials. The section further details the research questions, data collection strategy, and evaluation approaches adopted to assess transferability, replicability, and socio-economic impacts, including the design of expert and stakeholder questionnaires. *Section 4* reports the implementation of Mini-trial activities across the ICARIA CSs. For each CS, it describes the application of the risk/impact modelling framework to selected hazard scenarios, including the underlying input data, key assumptions, and modelling procedures. The section also integrates the output and results of the modelling activities with insights collected through expert and stakeholder questionnaires. Finally, the *Conclusions* summarise the main findings of the deliverable, highlighting key lessons learned from the activities carried out under Task 4.3.

The results presented in Deliverable 4.3 provide a key contribution to the validation of the ICARIA project outcomes and demonstrate the achievement of **Milestone 3 – Trial assessment and replication**, as defined in the DoA. In particular, the activities and findings reported in this deliverable contribute to the fulfilment of several Key Performance Indicators (KPIs) associated with Task 4.3. These include:

- **KPI1.2** – Implementation of the testing methodology across all ICARIA CSs, including both full Trials and Mini-trials;
- **KPI3.2** – Validation of data gap and uncertainty management methods through stakeholder feedback collected during the Mini-trial phase;
- **KPI4.2** – Successful replication of the ICARIA modelling framework within the Mini-trial activities;
- **KPI5.2** – Implementation and replication of multi-risk and resilience assessment approaches across the ICARIA CSs, supported by stakeholder evaluation.

Through the achievement of these KPIs, Deliverable 4.3 contributes to the accomplishment of key SSOs of the project, specifically SSO1, SSO3, SSO4, and SSO5, as introduced in Section 1 of this document.

### 3. Transitioning from Trials to Mini-trials

#### 3.1. Overview of the Trial Guidance Methodology

The ICARIA testing and validation process builds upon and extends the **Trial Guidance Methodology** (Fonio et al., 2020; 2023), originally developed and successfully tested within the DRIVER+ project - DRiving InnoVation in crisis management for European Resilience, 2014-2020 (FR7 programme, Grant agreement ID: 607798, 2014-2020).

TGM is a structured methodology designed to assess the innovation potential of socio-technological solutions for specific stakeholders or stakeholder organisations. It adopts a **systemic approach to evaluating novel solutions designed to address targeted societal or organisational needs (gaps)**. The TGM Handbook (Fonio et al., 2023) provides comprehensive, step-by-step guidance for designing and implementing Trials, clearly defining roles and responsibilities and outlining a coherent set of activities, methods, and tools to support implementation, outcome evaluation, and the identification of lessons learned. TGM ensures a rigorous, systemic process that enhances the transferability and replicability of results while remaining sufficiently flexible to adapt to different operational contexts.

Structurally, TGM organises the Trial process into three main phases: **preparation, execution, and evaluation**. Each phase is further articulated into specific steps and complemented by practical examples supporting the planning, implementation, and assessment of the process, as detailed in Table 1.

**Table 1.** DRIVER+ Trial Guidance Methodology – all steps.

DRIVER+ Trial Guidance Methodology		
Step Zero	Gaps	Identification of current problems and needs that the stakeholders are facing.
	Trial context	Comprehensive description of the gap-specific aspects and factors.
Preparation	Trial objective	Defining the specific goals and desired Trial achievements, based on SMAR criteria (Specific, Measurable, Achievable/Attainable, Relevant/Reasonable, Time-bound).
	Research question	Formulating a research question on what is wanted to find out in the context of these Trials specifically.
	Data collection plan	Detailed plan on what data must be gathered to answer the research question, including the methods required for how the data will be acquired.
	Evaluation approaches & metrics	Analysis and evaluation of the gathered data, previously defined in the data collection plan.
	Scenario formulation	Developing a simulated real-life situation in which the addressed gap occurs, depending on the gap and Trial-specific underlying conditions.
	Solution selection	Selecting a reasonable and manageable number of solutions and aspects that have to be tested.
Execution	Trial integration meeting	Discussion with the Trial participants on how the solutions will be integrated into the tester's operations.

DRIVER+ Trial Guidance Methodology		
	Dry run 1	First test run of the Trial.
	Dry run 2	Second test run (full test) of the Trial.
	Trial run	Execution of the planned Trial.
<b>Evaluation</b>	Data quality check	Identification of possible deviations in the data.
	Data analysis	Analysis and evaluation of the gathered data.
	Data synthesis	Discussing the data with the CoPs to gain further insights and conclusions.
	Disseminate results	Formulating lessons learned and possible adaptations for the Mini-trials and demos.

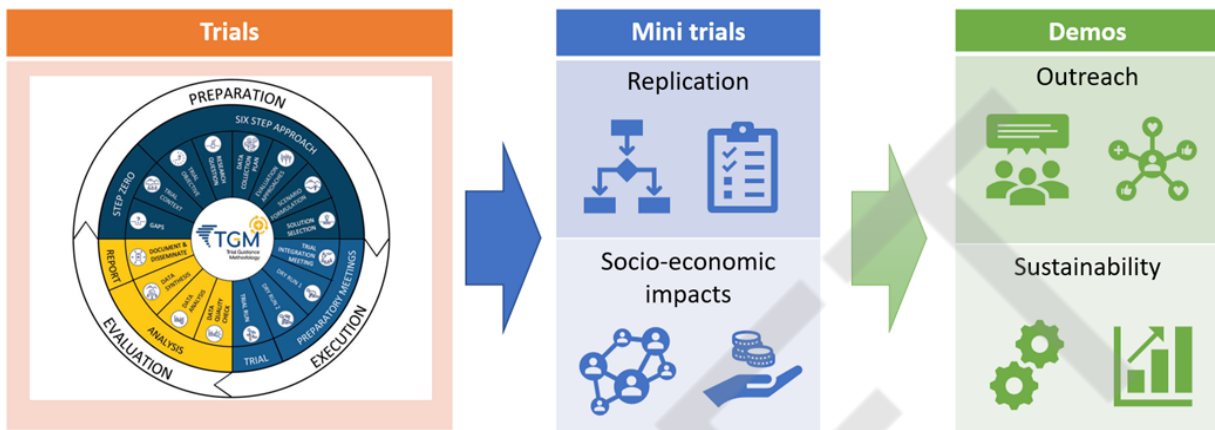
Thanks to its generic nature, TGM has already been successfully applied in multiple H2020 and HE projects (Fonio et al., 2023) and has entered a standardisation process through the publication of the CEN Workshop Agreement CWA 17514 (CEN-CENELEC Management Centre, 2020). Although originally designed for crisis management contexts, its successful application in the RESILOCC3 - Resilient Europe and Societies by Innovating Local Communities project demonstrates that TGM can be applied in broader societal resilience settings with only minor adaptations.

From the ICARIA perspective, **TGM provides a robust framework for ensuring objective evaluation of project results by requiring the prior definition of gaps to be addressed**, together with **the corresponding objectives and research questions guiding Trials**. It also mandates **the up-front specification of the data to be collected** and of the **methodological approach through which these data will be analysed and interpreted**. In the context of ICARIA, Deliverable 4.3 corresponds to the evaluation phase of the TGM, summarising the results and lessons learnt during Trial execution, while further extending the validation process through the implementation of Mini-trials and demonstration activities.

An essential feature of TGM is the **active involvement of key stakeholders** throughout the Trial process, including preparation, execution, and evaluation phases. This participatory approach ensures that Trials are grounded in real operational needs and that the intended users validate their outcomes. In ICARIA, this participatory logic is operationalised through **Communities of Practice (CoPs)** – which establish a structured link between the core Trial team and relevant stakeholders – and, more specifically, through CoP events, as defined in Section 4 of Deliverable D5.4 – “Stakeholder Engagement Plan” (Turchi et al., 2023b).

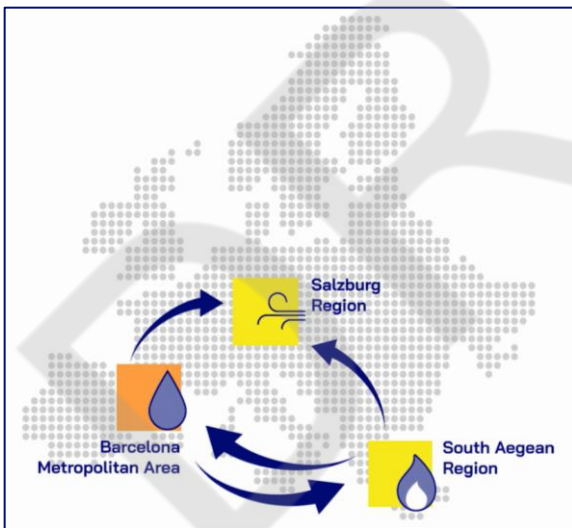
### 3.1.1. Scope and objective of the ICARIA Mini-trials

Building upon the methodological foundations of the TGM described above, Mini-trials represent a structured extension of the ICARIA testing and validation process (Figure 1).



**Figure 1.** Overarching ICARIA methodology for assessing the solutions developed in the project (see Deliverable 4.1; Havlik et al., 2024).

While fully grounded in the principles, structure and logic of the TGM – retaining its core phases and steps – **ICARIA Mini-trials are conceived as streamlined and ‘lightweight’ versions of the full Trials.** They are characterised by a more focused scope and a simplified operational design, tailored to the specific objectives of Task 4.3.



**Figure 2.** Derivation of ICARIA Mini-trials from the Trial architectures, illustrating their adaptation and simplification to support transferability and replicability.

Rather than being designed from scratch, **Mini-trials in most cases build upon the Trial architectures** developed and implemented in Task 4.2, which are adapted and simplified to serve transferability/replicability purposes (Figure 2). However, **in some cases, Mini-trials represent stand-alone simplified assessments,** not directly derived from a prior Trial.

Therefore, ICARIA Mini-trials represent a specific configuration of the TGM, one that entails a **substantive redefinition of objectives** with respect to the full Trials. While the primary objective of the ICARIA Trials was to assess the capability of the ICARIA models and tools to enhance the understanding of climate resilience and climate change preparedness among local risk owners (authorities and critical asset operators) –

by simulating the extreme multi-hazard events and related risks/impacts on critical infrastructures, as well as supporting adaptation decision-making – the **overarching objectives of the Mini-trials** are twofold:

- 1) to assess the potential **transferability of the ICARIA methods and tools across CSs** (e.g., including software, modelling procedures, ICARIA toolkit, etc.) and **replicability in new geographical, hazard, risk/impact, and governance contexts**, or alternatively to **implement stand-alone simplified assessments** where no prior Trial framework is directly transferable/replicable;
- 2) to evaluate the potential **socio-economic impacts associated with the application of ICARIA solutions and recommendations**.

These two dimensions are intrinsically interlinked, as the broader applicability and added value of the ICARIA modelling framework rely equally on each of them.

The relevance of the five original Trial objectives within the Mini-trial framework is presented in Table 2. Trial objectives – closely linked to identified gaps and formulated according to SMART criteria, as established in Deliverable 4.1 (Havlik et al., 2024) – define the overarching goals and aspirations of the Trial team and remain unchanged throughout project implementation. Table 2, therefore, illustrates the extent to which each objective continues to apply in the Mini-trial context, distinguishing between aspects already validated during the main Trials and those requiring further assessment.

**Table 2.** Relevance of ICARIA Trial objectives for Mini-trials.

	Objective No.	Relevance
O1	Validate the <b>plausibility of ICARIA data and modelling results (hazards, impacts, damage estimates, adaptation impacts)</b> .	This objective and related research questions have already been validated in Trials. What remains to be done is validating the plausibility of the transferred data and models, especially when a simplified modelling methodology or proxy datasets are used.
O2	Validate the <b>appropriateness (relevance, effectiveness, side effects, societal justice) of the adaptation measures</b> suggested by ICARIA solutions.	This has been partially achieved in the Trials and should be followed up on in the Mini-trials, and even in the final demonstration event(s).
O3	Validate the <b>capability of proposed adaptation measures to reduce impacts</b> .	Already validated in the Trials. What could be further examined are the opinions of stakeholders and potential region-specific variations.
O4	Validate the <b>capability of the ICARIA tools and models to simulate the impact associated with the long-term changes in weather patterns (caused by climate change) on critical infrastructures</b> .	This has been validated in Trials. What could be further examined is how this capability changes if simplified models and proxy datasets are used instead of the highest quality data.
O5	Assess to what extent/how the ICARIA data/models/tools can help regional authorities and other stakeholders to <b>assess the Climate Change</b>	Already validated in Trials. Further insights into the interest and willingness of stakeholders to use the ICARIA

Objective No.	Relevance
<b>(CC) vulnerability/resilience (strengths and weaknesses) of their critical infrastructures.</b>	methodology and solutions for assessing the CC vulnerability beyond the end of the project (impacts, sustainability) should be further examined.

The ICARIA Trial objectives were operationalised through three CSs, each centred on the analysis of relevant assets – not limited to critical infrastructures – within three distinct territorial contexts: the alpine **Salzburg Region in Austria (SLZ)**, the Mediterranean archipelago of the **South Aegean Region in Greece (SAR)**, and the highly densely populated **Barcelona Metropolitan Area in Spain (AMB)**. These CSs provided the empirical basis for evaluating the transferability of the results achieved in Task 4.2, as well as for validating these results through replication in diverse geographical, hazard, risk/impact and governance conditions across the Mini-trials.

In operational terms, this involves either exploring how selected ICARIA methods and tools, as well as solutions and recommendations, can be adapted and applied elsewhere – as in the case of the wildfire scenario within the AMB and SLZ CSs, as well as the flood scenario within the SAR CS – or directly applying a simplified methodology where no prior Trial framework is transferable – as in the case of the drought scenario within the AMB CS, as well as and the heatwave scenario within the AMB and SLZ CSs. In the latter cases, the process involved an **explicit knowledge and approach transfer across CSs**, representing a more substantial form of transferability than the mere application of a simplified methodology.

The specific focus of each Mini-trial was defined in line with priorities and interests identified by the respective Trial teams:

- **AMB:** Mini-trials focus on **drought, heatwave, and wildfire** scenarios under climate Socioeconomic Pathways (SSPs), specifically SSP1-2.6 and SSP5-8.5. Drought impacts are primarily assessed in relation to water resource variation, which has further environmental and social consequences, and socio-economic repercussions for water-dependent sectors (agriculture, industry, and services). Heatwave impacts are assessed in relation to sustained increases in air temperature, which lead to intensified thermal stress in urban environments, resulting in adverse impacts on human health and critical infrastructures such as transport and electricity networks. Wildfire impacts are assessed in relation to dry and hot conditions, which are often combined with wind, creating a favourable setting for fire ignition and resulting in impacts on natural areas;
- **SLZ:** Mini-trials address **heatwave and wildfire** scenarios under climate SSP1-2.6 and SSP5-8.5. Heatwave impacts are assessed in relation to sustained increases in air temperature, which lead to intensified thermal stress in urban/extra-urban environments, mainly resulting in adverse impacts on human health. Wildfire impacts are assessed in relation to dry and hot conditions, which are often combined with wind, creating a favourable setting for fire ignition and resulting in impacts on natural areas;

- **SAR:** Mini-trials concentrate on **flood** and **extreme wind** scenarios under climate SSP1-2.6 and SSP5-8.5. Flood impacts are assessed in relation to prolonged heavy rainfall leading to pluvial flood events, resulting in impacts to properties and critical infrastructures such as water distribution and wastewater systems. This leads to service disruption and socio-economic repercussions for water-dependent sectors (e.g., tourism). Extreme wind impacts are assessed in relation to sustained high wind conditions, mainly resulting in impacts to maritime transport and subsequent service disruption and socio-economic repercussions for transport-dependent sectors (e.g., tourism).

This approach ensures that replication priorities and pathways are defined in a context-sensitive manner, while maintaining methodological coherence across CSs.

### 3.1.2. Mini-trial design and implementation approach

**ICARIA Mini-trials are conceived as a simplification and specialisation of the Trial approach** adopted under Task 4.2. building upon the methodological foundations described in Deliverable 4.1 (Havlik et al., 2024) and Deliverable 4.2 (de la Cruz Coronas et al., 2026), while adapting specific components of the TGM to the objectives of Task 4.3. As outlined above, their design follows two distinct configurations – adaptation of existing Trial architectures for transferability and replicability purposes, or a stand-alone simplified assessment. Across both, socio-economic impact assessment is consistently embedded as a transversal objective, pursued in all Mini-trials regardless of their specific design.

From a structural perspective, ICARIA Mini-trials adhere to the three main TGM phases – preparation, execution, and evaluation – but apply them in a more focused and operationally streamlined manner. The core logical sequence of defining objectives, formulating research questions, planning data collection and evaluating results remains unchanged. However, **the scope of validation shifts from comprehensive tool testing towards transferability-/replicability-oriented assessment as well as socio-economic impact analysis.** In this context, hands-on technical validation of ICARIA software by event participants is not necessarily a prerequisite within a Mini-trial. Rather than emphasising detailed testing of individual tools, Mini-trials concentrate on evaluating the feasibility, added value and implications of applying ICARIA methods and tools in diverse geographical, hazard, risk/impact, and governance contexts. They also provide an opportunity to clarify further or refine research questions that were not fully resolved during the main Trials, as reported in Deliverable 4.2 (de la Cruz Coronas et al., 2026).

In addition to the Mini-trials, ICARIA foresees **demonstration activities** that contribute to the overall validation and consolidation of project results (Figure 1). The demonstration typically represents the “feel well” final project event, during which the consolidated ICARIA outcomes from Trials and Mini-trials are presented to relevant stakeholders, including actors beyond CoPs, highlighting their practical applicability, potential benefits, and added value. The event provides an opportunity to demonstrate the capabilities of ICARIA methods and tools, foster outreach towards potential end-users, and evaluate stakeholders’ interest in the replication elsewhere. In this context, particular attention is given to discussing the exploitation potential and long-term sustainability of the project outcomes with participants. This demonstration is implemented through the Final Event, organised

under Task 5.4 – “Stakeholders Engagements” (see Deliverable 5.4; Turchi et al., 2025b), which provides the stakeholder engagement and outreach framework. While the demonstration is part of Task 4.3, its practical organisation and facilitation are led under WP5, in close coordination with WP4. It therefore complements the broader project validation framework while remaining distinct from the Mini-trial activities in terms of scope and governance.

### 3.1.3. Mini-trial research questions

**Research Questions (RQs) represent the core analytical backbone of both Trials and Mini-trials.**

Throughout the Trial process, they connect different methodological components, as they address specific gaps, must be answerable in an objective manner within the Trial setting, and need to be clearly understood and agreed upon by all Trial stakeholders. Well-formulated research questions are expressed in a simple and easy-to-understand way and maintain a clear relationship with the identified gaps and the corresponding Trial objectives.

Within the ICARIA project, research questions were originally defined in Deliverable 4.1 (Havlik et al., 2024; Table 3). These questions remained unchanged throughout the Trial execution phase, as they proved to be methodologically sound and analytically relevant for evaluating the overall ICARIA modelling framework, methods, tools, as well as the stakeholder engagement processes. To ensure analytical coherence across CSs, the ICARIA Trial teams grouped the RQs into four main dimensions, valid for both Trial and Mini-trials:

- **[Sci] Science and technology** (e.g., “how good are the model predictions?”; “How well does the DSS work?”);
- **[Ux] User experience** (e.g., “How much training do potential users need to use the solutions?”);
- **[Acc] User acceptance and sustainability** (e.g., “Do potential users want to use this type of solution in their work?”; “How well do the solutions support their decision-making process?”);
- **[Soc] Socio-economic impacts and ethics** (e.g., “What socio-economic impacts do CoP members anticipate from trialled solutions?”; “How do proposed adaptations contribute to just transition?”).

Table 3 shows how relevant each original Trial research question is within the Mini-trial framework, distinguishing between aspects that have already been sufficiently validated during the main Trials and those requiring further examination in the context of possible transferability-/replicability-oriented assessment. Although Mini-trials build upon the methodological foundation of the Trials, they introduce additional research questions – **[Sus] Sustainability** – tailored to the objectives of Task 4.3. These are designed to complement and extend the original set of questions, with a particular emphasis on transferability and replicability potential.

**Table 3.** Relevance of ICARIA Trial research questions for the Mini-trials.

Research Question No.		Relevance
RQ-Sci1	How plausible/reliable are ICARIA data/modelling results?	<b>Medium relevance:</b> plausibility of transferred results needs to be examined.
RQ-Sci2	How easy/difficult/expensive would it be to apply the ICARIA solutions in new regions?	<b>High relevance:</b> this reflects one of the main goals of Mini-trials.
RQ-Sci3	Which data/modelling aspects of ICARIA solutions need to be further developed/improved?	<b>Medium relevance:</b> Mini-trials should be used to improve our understanding of stakeholders' needs and wishes concerning this topic.
RQ-Sci4	To what extent does the functionality of the ICARIA tools go beyond the state of the art/what is currently used in the region?	<b>Medium relevance:</b> Mini-trials should be used to improve our understanding of the regional SOTA (State Of The Art) as it is at the end of the project, and of the perceived value of different features.
RQ-Ex1 (Ux)	How easy or difficult is it to use the solutions?	<b>Low relevance:</b> this aspect has been sufficiently validated through the Trials, but additional information can be gathered if opportune.
RQ-Ex2 (Ux)	How easy or difficult is it to understand the results/recommendations offered by the solutions?	<b>Low relevance:</b> this aspect has been sufficiently validated through the Trials, but additional information can be gathered if opportune.
RQ-Ex3 (Ux)	What needs to be done to improve the user experience/usability of the solutions?	<b>Medium relevance:</b> this aspect has been sufficiently validated through the Trials, but additional information can be gathered if opportune.
RQ-Acc1	How useful is the ICARIA methodology for the regional authorities and other stakeholders?	<b>Medium relevance:</b> this aspect has been partially validated through the Trials, but additional information could/should be gathered, with a clear differentiation between the perceived usefulness of the methodology and solutions.
RQ-Acc2	How useful are ICARIA solutions for the Regional Authorities and other stakeholders?	<b>Medium relevance:</b> same as RQ-Acc1.
RQ-Acc3	Do potential users want to use this type of solution in their work?	<b>Medium relevance:</b> this aspect has been partially validated through the Trials, but we need a better understanding of the level of interest and willingness of the stakeholders to invest in ICARIA solutions beyond the project end.
RQ-Acc4	Which improvements/additional features would make the ICARIA methodology and/or solution(s) significantly more attractive for potential users?	<b>Medium relevance:</b> this aspect has been partially validated through the Trials, but we need a better understanding of the level of interest and willingness of the stakeholders to invest beyond the project end.

Research Question No.		Relevance
RQ-Soc1	How much socio-economic impact (including gender and ethics issues) do Trial participants anticipate from ICARIA methodology and solutions?	<b>High relevance:</b> validating the socio-economic impacts is one of the key Mini-trials objectives, and this aspect has not been validated in the Trials.
RQ-Soc2	What kind of socio-economic impacts (including gender and ethics issues) do Trial participants anticipate from the use of ICARIA methodology and solutions?	<b>High relevance:</b> validating the socio-economic impacts is one of the key Mini-trials objectives, and this aspect has not been validated in the Trials.
RQ-Sus1	Are potential users willing to pay for ICARIA solutions?	<b>High relevance:</b> assessing users' willingness to pay is essential for evaluating the sustainability of ICARIA solutions beyond the project, a core objective of the Mini-trials, which has not yet been systematically validated across trial contexts.
RQ-Sus2	Are potential users willing to wait for ICARIA solutions to be tailored to other contexts?	<b>High relevance:</b> assessing users' tolerance for adaptation waiting time directly tests the transferability and replication feasibility of ICARIA solutions to new regions with limited data/resources, representing a key Mini-trials objective that remains unvalidated in the Trials.

### 3.1.4. Mini-trial data collection plan

As indicated in Deliverable 4.2 (Section 3.4.4; de la Cruz Coronas et al., 2026), several data collection methods were originally designed and implemented within the ICARIA Trials. **In the context of the Mini-trials, these methods are not redefined** but rather reassessed in terms of their relevance and applicability to the specific objectives of Task 4.3. The relevance of each method for the Mini-trial is summarised in Table 4.

**Table 4.** Relevance of ICARIA Trial data collection methods for the Mini-trials trials.

Method	Use in Trials	Use in Mini-trials
Scientific validation	Significant efforts were dedicated to the implementation and validation of the <b>modelling methodology and resulting data</b> by the project team.	The ICARIA team should invest <b>modest efforts</b> to assess the simplified methodology. An <b>expert questionnaire</b> needs to be administered to Case Study Facilitators (CSFs) to assess modelling-related aspects and cost estimates behind transferability and replicability.
Observers	Significant efforts were dedicated to the implementation of <b>tutorial scripts, observer questionnaires,</b> and the organisation of the <b>hands-on testing.</b>	Observers are an <b>optional feature</b> for the Mini-trials. Since no hands-on testing of the solutions is foreseen, they could (should) only be used to observe the whole demonstration event and <b>write down stakeholders' informal reactions and suggestions</b> that would not be captured otherwise.

Method	Use in Trials	Use in Mini-trials
<b>Stakeholder Surveys</b>	Significant efforts were dedicated to the implementation of <b>stakeholder questionnaires</b> , but the results were subpar.	An <b>improved stakeholder survey</b> needs to be developed, primarily addressing the Mini-trial objectives and high-priority research questions.
<b>Interactive surveys &amp; debriefings</b>	Mentimeter was used to organise <b>interactive feedback sessions</b> during the Trials, with good results, at least in the AMB Trial.	Recommended as a method to collect information complementary to that obtained through a fully fledged survey, as well as a means to <b>engage stakeholders</b> , especially in the context of Mini-trials, where no hands-on testing of solutions is planned. (Mini-)trial owners are encouraged either to use <b>GDPR-compliant online survey methods</b> or to collect structured feedback through <b>offline facilitated validation and prioritisation sessions</b> (e.g., brainwriting, idea clustering, dot voting, or World Café formats).
<b>Interviews &amp; expert conversations</b>	Organisation of <b>interviews with a small number of key stakeholders</b> was recommended to Trial organisers, but wasn't used in the Trials due to a lack of time and high effort.	Recommendation to conduct <b>interviews with a small number of key stakeholders</b> remains for Mini-trials, especially for resolving the questions related to future investments/exploitation, as well as sustainability.

As illustrated in Table 4, **surveys represent one of the key data collection methods for the Mini-trials** under Task 4.3. **Two distinct but analytically aligned questionnaires were developed and administered**, targeting (i) project **experts** involved in the implementation of Trials and Mini-trials, and (ii) **stakeholders** engaged through the CoPs. While both questionnaires address transferability, replicability, and socio-economic dimensions, they do so from different perspectives, reflecting the distinct roles of technical implementers and potential end users.

The first questionnaire (see Annex I) targets project experts involved in the design, implementation, and facilitation of Trials and Mini-trials (i.e., CSFs, supported by modellers). Its purpose is to collect structured, experience-based evidence on transferability conditions, replication feasibility, and resource implications associated with the ICARIA modelling framework. The **expert questionnaire** was applied consistently across Mini-trials and completed separately for each event-tree representation (i.e., each modelled scenario), ensuring comparability of responses across different hazard and risk/impact configurations, as well as modelling contexts.

In line with the research questions defined for Task 4.3 (RQ-Sci1-4), it was designed to systematically collect qualitative and semi-quantitative evidence supporting:

- the **scientific feasibility of transferring the ICARIA modelling framework across CSs**, as well as **replicating it in different geographical, hazard, risk/impact, and governance contexts**;

- the **plausibility, reliability and empirical validation of ICARIA data and modelling results** when replicated;
- the **enabling and constraining technical conditions affecting transferability and replicability**, as well as **data and modelling components requiring further refinement or development**;
- the **expected effort and resource requirements**, including indicative cost ranges and implementation timelines, for replicating ICARIA results in other European regions and beyond;
- the level of **methodological and operational support required from the ICARIA toolkit**, including the Adaptation Portfolio, Resilient Assessment Framework (RAF), Resilient Assessment Tool (RAT), and DSS;
- the **anticipated socio-economic relevance and long-term sustainability of ICARIA solutions** beyond the project duration.

The second questionnaire (see Annex II) targets stakeholders engaged through the CoPs. Its purpose is to validate the relevance and usability of ICARIA results through demonstration-oriented feedback and explore interest in potential follow-up, replication, and exploitation activities. The **stakeholder questionnaire** was likewise administered in relation to both Trials and Mini-trials, taking into account key thematic dimensions identified during the expert survey in order to ensure conceptual coherence.

In line with the research questions defined for Task 4.3 (RQ-Sci1, RQ-Ex1-3, RQ-Acc1-4, RQ-Soc1-2 and RQ-Sus 1-2), the stakeholder questionnaire was designed to systematically collect qualitative and semi-quantitative evidence supporting:

- the **perceived plausibility and technical feasibility of transferring the ICARIA modelling framework across CSs** as well as **replicating it in different geographical, hazard risk/impact, and governance contexts**;
- the **enabling and constraining organisational, institutional, and strategic conditions** affecting the potential adoption and replication of ICARIA solutions;
- the **perceived affordability and acceptable investment conditions**, including stakeholders' willingness to pay, acceptable cost ranges, and preferred implementation timelines;
- the **perceived usability, clarity of results and recommendations, integration needs, and preferred operational support requirements** related to the ICARIA toolkit (Adaptation Portfolio, RAF, RAT, and DSS), as conditions for effective adoption;
- the **anticipated socio-economic relevance, equity implications, and long-term sustainability** of ICARIA solutions beyond the project duration.

The structure, rationale, and administration of the expert and stakeholder questionnaires are described in Sections 3.1.4.1 and 3.1.4.2, respectively, while the evaluation approach and metrics are presented in Section 3.1.4.3.

#### 3.1.4.1. Expert questionnaire design

The expert questionnaire is structured to systematically assess the transferability of the ICARIA modelling framework across CSs and validate its results through replication, taking into account direct implementation experience gained in both Trials and Mini-trials. While the primary evidence derives from Mini-trial execution, the inclusion of Trial-based assessments provides an additional layer of technical validation, grounded in first-hand modelling experience, thereby strengthening the robustness of the analysis.

In line with the objectives of Task 4.3, its design translates the analytical dimensions of transferability and replicability into a set of thematically organised sections that guide respondents through the key technical, operational, and resource-related aspects of framework implementation. The questionnaire is organised into five main sections: the respondent profile (Section 1); an overview of the ICARIA modelling framework (Section 2); model setup, data requirements and expected outputs (Section 3); DSS integration (Section 4); as well as replication effort and resource requirements (Section 5).

##### Section 1 – Expert profile

This section collects background information on the respondent's role, organisation, domains of technical expertise, and level of familiarity with the ICARIA modelling framework (*Questions 1-6*). This information is used to contextualise the technical assessment provided in the subsequent sections, ensuring transparency regarding the level and type of expertise underpinning the survey responses and supporting the interpretation of results in relation to the respondent's direct involvement in Trial and Mini-trial activities.

##### Section 2 – Framework overview

This section characterises the hazard and risk/impact scenarios implemented within Mini-trials through the ICARIA modelling framework, with explicit reference to the event-tree representation. It describes the relationship among hazards (compound coincident or consecutive), the elements at risk, and the possible cascading effects (*Question 7*). It further addresses the spatial and temporal scales of application and gathers expert judgement on the key factors and/or limitations influencing the successful replication of the framework in other contexts (*Questions 8-10*).

##### Section 3 – Model setup, data requirements and outputs

This section investigates the requirements for transferring and replicating the ICARIA modelling workflow, addressing the effort needed for input data preparation, the sensitivity to both data quality and resolution, and the main data-related barriers (*Questions 11-13*). It also describes the expected output datasets and the range of adaptation measures that can be modelled through alternative runs (*Questions 14-15*). This information provides core evidence on practical and technical feasibility, including minimum data requirements, common data challenges, and the relevance and usability of model outputs in support of decision-making and adaptation planning.

##### Section 4 – DSS integration

This section describes how the ICARIA DSS supports the modelling workflow, identifying workflow stages that are fully or partially supported (*Questions 16-17*). It clarifies the role of the DSS in enabling

transferability and replicability of the ICARIA modelling framework and informs the assessment of associated efforts and resource requirements.

#### Section 5 – Replication effort and resource requirements

This section addresses the economic, temporal, and organisational aspects of transferring and replicating the ICARIA modelling framework. It covers the main cost drivers, indicative cost ranges, typical implementation timelines, the most time-consuming implementation steps, and key obstacles that may affect transferability and replicability (*Questions 18-22*). The evidence collected provides structured information on effort, costs, and constraints, thereby supporting the transferability, replicability, and related sustainability and exploitation considerations.

#### 3.1.4.2. Stakeholder questionnaire design

The stakeholder questionnaire is structured to capture the perspectives, interests, and expectations of local authorities and other relevant actors regarding the use of the ICARIA methods and tools beyond the project team, while supporting demonstration activities and potential follow-up initiatives under Task 4.3. The questionnaire is organised into eight main sections, each responding to specific aims related to stakeholders' interest in ICARIA solutions, their relevance outside the consortium, and the conditions for supporting replication, demonstrations, and exploitation pathways: the respondent profile (Section 1); organisational needs and priorities (Section 2); knowledge and use of the existing hazard and risk/impact assessment tools (Section 3); plausibility and reliability of ICARIA data and modelling results (Section 4); interest in the ICARIA modelling framework (Section 5); interest in the DSS component (Section 6); willingness to support the replicability of the ICARIA framework (Section 7); as well as socio-economic, gender and ethics impacts (Section 8).

#### Section 1 – Respondent profile

This section collects basic information on the respondent's organisation, role, geographical level of competence, and prior experience in climate change and disaster risk management (*Questions 1-4*). These variables allow the interpretation of the stakeholders' interest and perceived relevance of ICARIA solutions in relation to institutional mandates and capacities, and to identify which organisational profiles are more likely to support or engage in follow-up activities.

#### Section 2 – Organisational needs and priorities

This section aims to characterise the main climate-related hazards of concern, the frequency of climate risk/impact assessments, and the priority sectors for the respondent's organisation (*Questions 5-7*). By linking the identified hazards, risks/impacts, and sectoral priorities to the potential use of ICARIA modelling outputs, it provides insights into how ICARIA results are most aligned with existing needs, thereby indicating the contexts in which stakeholders may be more likely to request demonstrations and consider future replication.

#### Section 3 – Knowledge and use of existing risk/impact assessment tools

This section explores whether respondents currently use digital tools or platforms for climate risk/impact assessment, and perceived main limitations (*Questions 8-9*). It aims to identify gaps and needs that ICARIA could fill, and to assess the added value of ICARIA tools from the perspective of external stakeholders, thereby clarifying the potential for uptake beyond the project team and the

conditions under which stakeholders might support or co-invest in demonstrations and subsequent applications.

#### Section 4 – Plausibility and reliability of ICARIA data and modelling results

This section addresses stakeholders' perceptions of the credibility of ICARIA hazard and risk/impact maps for their territory, their level of trust in the input data used, and the aspects that would most increase their confidence in the results (*Questions 10-12*). By focusing on perceived reliability and conditions for enhanced trust, it directly supports Task 4.3 in evaluating whether stakeholders consider ICARIA outputs sufficiently robust to inform real-world decision-making processes and to motivate engagement in further demonstrations or replication efforts.

#### Section 5 – Interest in the ICARIA modelling framework

Considering both Trial (named ADVANCED VERSION) and Mini-trial (BASE VERSION) configurations, this section assesses stakeholders' perceptions of the usefulness and value of the ICARIA modelling framework, including its potential benefits for their organisation/territory, preferred use cases, the expected performance of such modelling tools compared to the existing ones, the ICARIA main value proposition relative to current approaches, and the level of satisfaction with data gap-filling methods adopted (*Questions 13-18 regarding the Trials; Questions 24-29 regarding the Mini-trials*). It also explores acceptable budget ranges for replication and potential funding sources, the justification and acceptability of different cost components, and the perceived technical demands of replication (*Questions 19-21 regarding the Trials; Questions 30-32 regarding the Mini-trials*). In addition, it addresses acceptable implementation timelines and the aspects of the ICARIA data and modelling approach that, in stakeholders' view, would require further development or improvement (*Questions 22-23 regarding the Trials; Questions 33-36 regarding the Mini-trials*). The evidence collected provides key insights into stakeholders' willingness to invest in and adopt the ICARIA tools, thereby informing Task 4.3 on the practical feasibility of replication and on the level of support that stakeholders may be prepared to mobilise for follow-up initiatives and demonstration activities.

#### Section 6 – Interest in the DSS component

This section investigates stakeholders' perceptions of the value of the DSS for integrating the ICARIA modelling workflows into their daily operational or planning processes, as well as the DSS-supported workflow components that would be most useful for their organisation (*Questions 37-38*). It further explores stakeholders' willingness to adopt the DSS as a standard tool for risk management and planning, the additional features that would increase their readiness to adopt it, and their priorities for future DSS development or enhancements (*Questions 38-41*). By focusing on adoption conditions and development needs, this section supports Task 4.3 in assessing the potential for exploitation and long-term use of the tool beyond the project.

#### Section 7 – Willingness to support the replicability of the ICARIA framework

This section examines stakeholders' willingness to contribute financially or with technical resources to the ICARIA outputs, as well as the types of contributions considered most feasible for their organisation. It also explores which additional results or applications would increase stakeholders' interest in the project outputs (*Questions 42-44*). The information collected provides evidence on the potential forms of support that stakeholders may be prepared to offer, thereby informing Task 4.3 on the prospects for replication and continued engagement beyond the project.

## Section 8 – Socio-economic, gender and ethics impacts

This section examines stakeholders' expectations regarding the potential positive socio-economic impacts of using the ICARIA methods and tools in their territory, including the types of impacts considered most likely (*Questions 45-46*). It also explores the extent to which ICARIA is perceived as contributing to gender and social equity in climate risk management, the groups that could benefit most from ICARIA-informed decisions, and any ethical concerns related to its use (e.g., data privacy, fairness, and the distribution of benefits and burdens) (*Questions 47-49*). By extending the assessment beyond technical performance to broader societal outcomes, it supports Task 4.3 in evaluating whether stakeholders view ICARIA methods and tools as relevant and legitimate for promoting equitable climate risk management, which in turn affects their willingness to endorse, promote, and co-support demonstrations and future replications beyond the project team.

### 3.1.4.3. Evaluation approaches and metrics

#### Expert questionnaire

The expert questionnaire was addressed to CSFs directly involved in the implementation of both ICARIA Trials and Mini-trials, with support from modelling experts where required. This purposive sampling strategy ensured that responses were grounded in first-hand technical and organisational experience of applying the ICARIA modelling framework across different CS contexts, covering different hazards and risk/impacts configurations, modelling setups, and DSS integration settings.

The questionnaire was administered *ad personam* via email during the implementation period of Task 4.3. This mode of administration allowed for targeted engagement with technically knowledgeable respondents and facilitated clarification of context-specific modelling aspects where necessary. To promote a consistent interpretation of questions across CSs, periodic follow-up exchanges were conducted, either bilaterally with individual CSFs or collectively with all CSFs, particularly to clarify technical aspects related to transferability and replicability conditions. Respondents could also refer to the online collaborative materials developed under Task 1.1 – “Risk/Impact Modelling Framework” (i.e., Miro boards: [link](#)) documenting hazard and risk/impact modelling processes through event-tree representations. These visuals provided a shared reference framework for the scenarios addressed in the questionnaire and supported overall methodological coherence across CSs.

The analysis of the expert questionnaire data combined descriptive summaries of responses to closed-ended questions with qualitative coding of explanatory comments and open-ended inputs. It was explicitly structured to address the ICARIA research questions related to the scientific validity (RQ-Sci1-4). This mixed approach enabled the quantification of response patterns at the Mini-trial level, while also supporting an in-depth interpretation of transferability and replicability conditions, with particular attention to the modelling workflow for hazard and risk/impact assessment, technical and data-related constraints, enabling factors, and key cost and time drivers influencing replication feasibility.

**Closed-ended question** items were analysed through structured case-based interpretation, reflecting the context-specific nature of expert inputs. Given that a single response was collected per

CS, the analysis did not aim to aggregate statistics or conduct direct cross-case comparisons. Instead, responses were examined within each region to identify:

- items concerning the structure and logical consistency of the targeted event-tree scenario(s) – including the representation of spatial and temporal relationships, interactions among hazards/exposure/vulnerabilities, as well as possible direct/indirect damage and cascading effects – alongside expert assessments of the framework’s dependence on input data quality, interpretability and usability of its outputs, the feasibility of simulating adaptation measures, and the DSS support across all workflow components (i.e., ‘elementary bricks’). Together, these elements provide evidence of the internal coherence and methodological soundness of the ICARIA modelling framework across its full analytical steps, thereby directly informing **RQ-Sci1** about the scientific plausibility and reliability of its results, while also highlighting the structural complexity that may influence replication conditions under **RQ-Sci2**;
- items addressing data requirements and broader technical constraints – including estimated data preparation effort, data-related barriers (e.g., resolution limitations, restricted access, missing variables), preprocessing and harmonisation needs, computational demands, as well as spatial and/or temporal scalability limits – characterising the framework’s structural sensitivity to contextual conditions and highlighting priority areas for methodological refinement and further development in line with **RQ-Sci3**, while also informing the practical feasibility of replication under **RQ-Sci2**;
- items examining enabling conditions for replication – particularly the extent to which the DSS supports the full modelling workflow, including the degree of methodological standardisation, system integration, modularity of modelling components, and the capacity to operationalise multi-hazard risk/impact analyses – assessing the operational maturity and architectural coherence of the ICARIA modelling framework. This strand of analysis directly informs **RQ-Sci2** by evaluating the practical ease with which the system can be applied in new contexts, while also contributing to **RQ-Sci4** by clarifying the added functional value of ICARIA tools compared to conventional multi-hazard/impact assessment approaches;
- items addressing cost implications, implementation timelines, and resource requirements – including identified cost drivers, estimated overall financial effort, anticipated duration, resource-intensive steps, and potential organisational or technical obstacles – thus defining the overall effort associated with replicating the ICARIA modelling framework to new contexts. This standard of analysis directly informs **RQ-Sci2** by providing structured evidence on the expected economic, temporal and organisational feasibility of its application.

**Open-ended question** responses and explanatory comments accompanying closed-ended items were examined through a focused thematic coding approach anchored in the ICARIA research questions. Given the technical and case-specific and technical nature of the qualitative inputs, coding aimed to clarify structural conditions, modelling assumptions, and replication constraints rather than to generate new conceptual domains. Relevant text passages were coded to reflect:

- descriptions of hazard and risk/impact configurations, including temporal sequencing, spatial relationships, interactions among hazards/exposure/vulnerabilities, and cascading effects, informing the assessment of scientific coherence under **RQ-Sci1**;
- explanations of factors influencing replication feasibility, including data preparation burdens, sensitivity to data quality and resolution, and technical limitations affecting model performance, refining the interpretation of **RQ-Sci2** and **RQ-Sci3**;
- clarifications regarding DSS workflow support and missing components, contributing to the assessment of operational maturity and functional integration under **RQ-Sci2** and **RQ-Sci4**;
- articulated obstacles likely to delay implementation or increase replication costs, providing qualitative depth to the analysis of economic and temporal feasibility under **RQ-Sci2**.

Rather than broadening the analytical scope beyond the predefined research questions, the purpose of this qualitative coding was primarily to contextualise and substantiate the findings derived from closed-ended responses. This ensured that assessments of plausibility/reliability, improvement needs, and replication effort were grounded in explicit technical explanations provided by experts.

#### Stakeholder questionnaire

The stakeholder questionnaire was addressed to participants in each CS workshop (CoPs), previously identified by CSFs as relevant stakeholders, ensuring coverage of key roles/sectors connected to the hazards and risks/impacts addressed. This sampling strategy ensured that responses were grounded in the specific CS contexts in which the ICARIA modelling framework was applied, reflecting different hazard and risk/impact settings as well as the range of modelling configurations discussed within each CS.

The questionnaire was administered via Google Forms and sent to the CSFs, who were responsible for forwarding it to the identified stakeholders. Administering this type of questionnaire through Google Forms represents an appropriate choice from both a methodological and an operational standpoint. The platform offers a flexible and user-friendly interface that helps reduce respondent burden, thereby increasing the likelihood of completion and supporting data quality. Its web-based nature enables rapid dissemination to geographically dispersed stakeholders, which is particularly relevant in multi-site projects such as ICARIA, where engaging diverse institutional actors across regions is essential. Moreover, the platform supports conditional logic and section-based navigation, allowing the questionnaire to be tailored to different stakeholder profiles while maintaining a coherent structure. This is particularly advantageous when addressing heterogeneous audiences (e.g., local authorities, technical agencies, NGOs), as it enables the collection of targeted information without overburdening respondents with non-relevant questions. At the same time, standardised digital delivery ensures data comparability across Trials and Mini-trials, reinforcing the robustness of cross-case analysis. Finally, using Google Forms enhances transparency and traceability in the data collection process. Timestamps, response tracking, and the possibility of duplicating and adapting forms for different events ensure consistent implementation across contexts, while also supporting documentation and auditability for reporting purposes.

At the beginning of the questionnaire, a brief description of the ICARIA project, its tools, and the overall purpose of the survey is provided, together with practical information on completion time and data protection. This introductory section sets the scene for stakeholders by clarifying that their responses will contribute to assessing the willingness to use ICARIA tools in practice and to guiding future replication and exploitation efforts, thereby directly linking participation to the objectives of Task 4.3 concerning post-project relevance and support to demonstrations. In addition, to facilitate completion and ensure consistent interpretation across CSs, Section 5 was rephrased using simplified terminology tailored to stakeholder understanding. In this section, Trials and Mini-trials are systematically presented as the “Advanced” and “Base” versions of the ICARIA methodology and tool application, respectively.

The analysis of the stakeholder questionnaire data combined descriptive summaries of responses to closed-ended questions with qualitative coding of responses to open-ended questions and was explicitly structured to address the ICARIA research questions on scientific validity, usability, acceptance, socio-economic relevance, and sustainability (RQ-Sci1–4, RQ-Ex1–3, RQ-Acc1–4, RQ-Soc1–2, RQ-Sus1–2). This mixed approach allowed for the quantification of response patterns at the Trial and Mini-trial level, while also enabling their interpretation in terms of underlying conditions influencing transferability and replicability beyond the project team.

**Closed-ended question** items were analysed using descriptive statistics, separately for each Trial and Mini-trial and, where relevant, in aggregate. For each item, absolute counts and percentage distributions of response options were computed, enabling fine-grained comparison of stakeholders’ positions across case studies and Mini-trial configurations:

- items on the credibility of maps and trust in input data were summarised to assess perceived plausibility and reliability of ICARIA outputs, thereby informing **RQ-Sci1**;
- questions on technical effort, cost acceptability, and implementation timelines (for Advanced and BASE VERSION) yielded distributions directly linked to **RQ-Sci2**, **RQ-Sus1**, and **RQ-Sus2**, by quantifying how many stakeholders regard replication as feasible, affordable, and temporally acceptable;
- items on required improvements in modelling aspects (e.g., hazard resolution, treatment of compound and cascading effects, economic damage modelling, uncertainty communication) were summarised by frequency of selection, addressing **RQ-Sci3** and highlighting priority areas for further development;
- comparisons with existing tools and judgments on strategic value were analysed to quantify the share of respondents perceiving ICARIA as equal to, somewhat better than, or significantly better than the state of the art, thus informing **RQ-Sci4**;
- ratings of ease of use, ease of understanding outputs, and interface/user-friendliness of the DSS were summarised to respond to **RQ-Ex1**, **RQ-Ex2** and **RQ-Ex3**, providing an empirical profile of user experience across contexts;

- perceived usefulness of ICARIA methodology and solutions, frequency and criticality of intended use, and willingness to adopt the DSS as a standard tool were analysed to address **RQ-Acc1**, **RQ-Acc2** and **RQ-Acc3**, by quantifying demand, intended operational integration, and adoption readiness;
- selections of desired DSS features and workflow components, as well as preferred improvements to methodology and tools, were summarised to identify the most frequently requested enhancements, thereby informing **RQ-Acc4**;
- items on anticipated socio-economic benefits, equity implications, and ethical concerns were described using distributions of response categories to respond to **RQ-Soc1** and **RQ-Soc2**, highlighting how strongly stakeholders expect ICARIA to generate positive socio-economic and equity-related impacts.

These descriptive summaries at the Trial and Mini-trial levels provided a structured and quantifiable mapping between stakeholder responses and the full set of research questions, enabling Task 4.3 to compare where and to what extent each RQ is positively or critically evaluated across contexts.

**Open-ended question** responses were analysed using a thematic coding framework that combined RQ-driven categories with inductively emerging themes. Text segments were coded to capture:

- conditions for transferability and replicability (e.g., data requirements, institutional preconditions, technical capacities), with particular attention to statements relating to effort, complexity, and feasibility, thus deepening the interpretation of **RQ-Sci2**, **RQ-Sci3**, **RQ-Sus1** and **RQ-Sus2** beyond the closed-item distributions;
- stakeholder needs and expectations regarding use cases, decision-making support, and integration into existing workflows, refining the understanding of **RQ-Acc1**, **RQ-Acc2** and **RQ-Acc3** in terms of concrete application domains and operational relevance;
- perceived barriers and enablers, including trust in data and models, clarity of outputs, usability of interfaces, organisational coordination, and governance constraints, complementing the quantitative evidence related to **RQ-Sci1**, **RQ-Sci4**, **RQ-Ex1-3** and **RQ-Acc4**;
- explicit and implicit references to cost drivers and resource constraints (e.g., data acquisition and harmonisation, calibration workload, technical integration, training and maintenance), which were thematically linked to **RQ-Sci2**, **RQ-Sus1** and **RQ-Sus2** by clarifying what stakeholders perceive as the main sources of cost and effort in replication;
- narratives on socio-economic, gender, and ethical implications, elaborating on the types of impacts and concerns associated with ICARIA-informed decisions, and enriching the interpretation of **RQ-Soc1** and **RQ-Soc2** with context-specific examples and conditions.

Codes were organised into higher-order themes aligned with the research-question clusters (i.e., scientific robustness, usability, acceptance, socio-economic impacts, and sustainability) and compared across Trials and Mini-trials. This thematic synthesis enabled the tracing of how

stakeholders' qualitative explanations underpin the quantitative patterns observed in closed-ended questions and facilitated the identification of recurring conditions under which ICARIA solutions are perceived as reliable, usable, attractive, and worth supporting in future replication and demonstration initiatives.

DRAFT

## 4. Implementation of “Mini-trial” impact models in CSs

### 4.1. Barcelona Metropolitan Area CS

This section presents the Mini-trials developed for the AMB CS within Task 4.3. In line with the overarching objectives of the Mini-trials, the AMB activities address drought, heatwave, and wildfire risk/impact modelling under climate change scenarios based on the SSPs framework (SSP1-2.6 and SSP5-8.5), with the dual aim of assessing transferability and replicability of the ICARIA methods and tools and evaluating the socio-economic implications arising from their implementation. The three hazard scenarios follow distinct design configurations: the **wildfire Mini-trial builds upon the Trial architecture developed and implemented within the SAR CS**, adapted and simplified to serve transferability and replicability purposes; the **drought and heatwave Mini-trials, by contrast, are implemented as stand-alone simplified assessments**, not directly derived from a prior Trial framework, and entail an explicit knowledge and approach transfer across CSs.

For each hazard type, Mini-trials describe targeted event-tree scenarios, spatial and temporal scales of application, key input data requirements and modelling assumptions, as well as the main outputs relevant for decision-making and adaptation planning. In addition to presenting the modelling results, the following subsections integrate evidence derived from both expert and stakeholder questionnaires administered during the Mini-trial phase. This combined presentation of modelling outputs, expert-based technical assessment, and stakeholder-based evaluations provides a structured basis for addressing Task 4.3 purposes.

#### 4.1.1. Drought impact and adaptation: modelling implementation

This section summarises the results of the drought hazard and economic impact assessment for the AMB CS over the period 15-Dec-2016 to 15-Dec-2098 (985 monthly observations). Monthly drought conditions were classified using the 12-month Streamflow Drought Index (SDI-12) into five categories: Normal (no drought), Mild, Moderate, Severe and Extreme. Results are reported for three climate model chains (M2\_ESM2\_0, CMCC\_ESM2 and CanESM5), each under SSP1-2.6 and SSP5-8.5. In the following, “drought months” are defined as all months classified as Mild/Moderate/Severe/Extreme (i.e., excluding Normal).

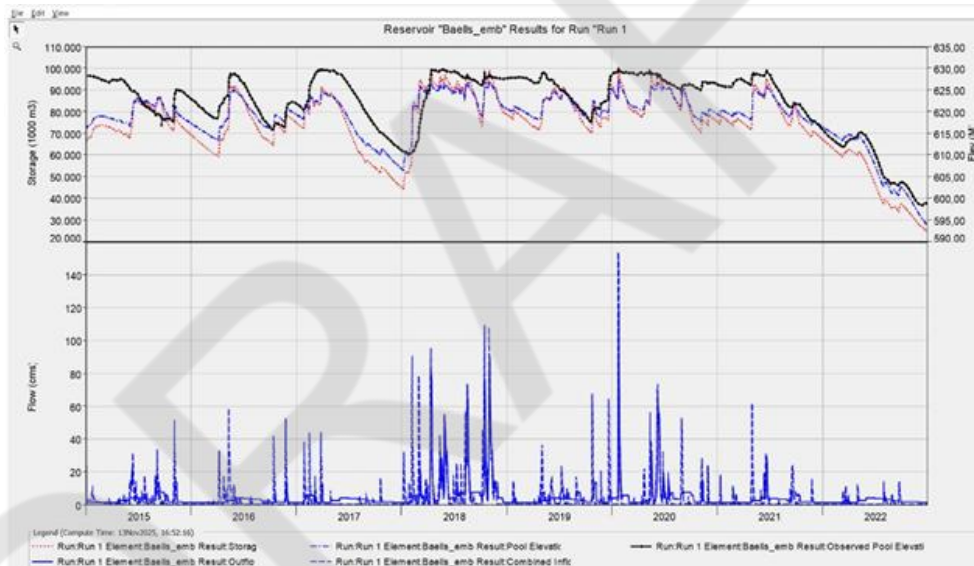
Drought conditions were translated into sector-specific economic shocks through a two-step procedure. First, monthly SDI-12 drought categories were mapped onto water restriction regimes consistent with the Catalan Special Action Plan in the Event of Alert and Drought (PES; Generalitat de Catalunya, 2020), which defines sector-specific reductions in guaranteed water supply under exceptionality and emergency scenarios. These reductions were converted into proportional output losses using econometric water–output elasticities estimated from a Cobb–Douglas production function via Seemingly Unrelated Regressions (SUR) (Freire-González, 2011). Second, these direct sectoral shocks were propagated through a supply-driven Input–Output model – the Ghosh (1958) model – regionalised to the AMB using the RAS method applied to the Catalan symmetric I-O table (IDESCAT, 2016). This framework captures both direct output reductions and indirect losses transmitted through interindustry linkages, enabling estimation of (i) the aggregate GDP impact and (ii) the distribution of production losses across economic sectors. Results are reported as cumulative

impacts over 2016–2098 in (a) undiscounted terms and (b) discounted Present Value (PV) using discount rates of 1%, 3% and 5%, reflecting common practice in long-term climate impact assessment and allowing sensitivity to social discounting assumptions.

### Hazard assessment results

Drought analysis of the Ter–Llobregat river system under climate change conditions was carried out using physically based hydrological models. This model was developed using free Hydrologic Engineering Centre - Hydrologic Modelling System (HEC-HMS) software (<https://www.hec.usace.army.mil/software/hec-hms/downloads.aspx>) and covers all the subcatchments providing surface runoff reaching the reservoirs of the Ter-Llobregat system. This system feeds, among other territories, the AMB.

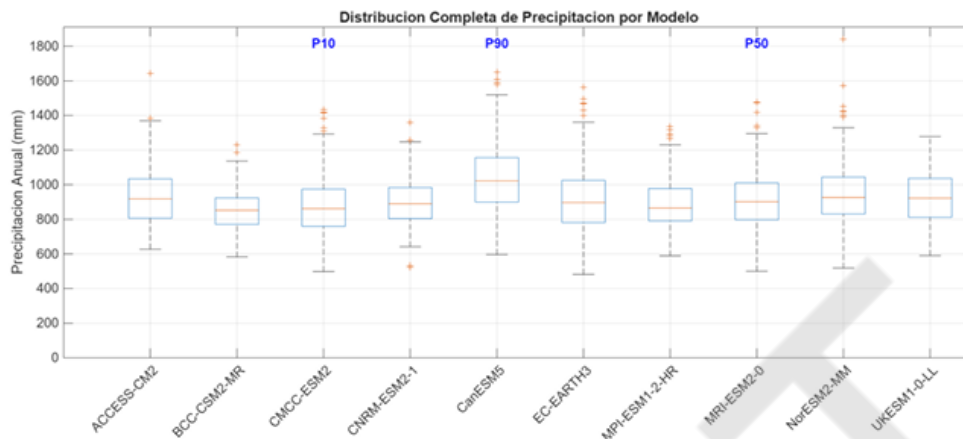
The model was calibrated using historical data provided by regional meteorological and hydrological agencies (Servei Meteorològic de Catalunya and Agència Catalana de l’Aigua). Data used for the model development and calibration included rainfall, temperature (to estimate evapotranspiration losses), flow discharges, reservoir water levels, and their exploitation rules (Figure 3).



**Figure 3.** Calibration of Baells reservoir with historic data.

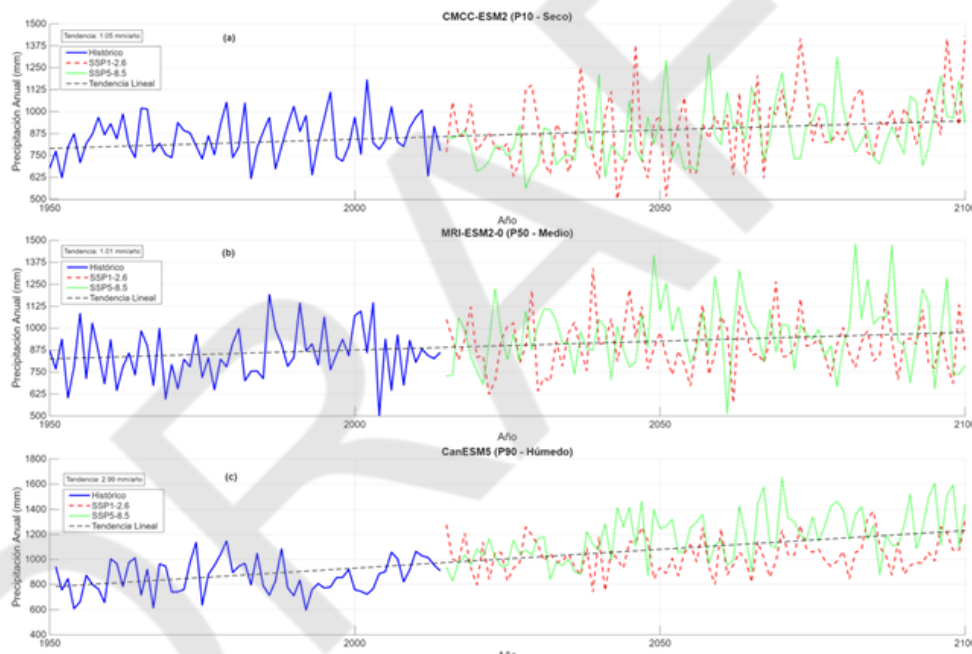
The analysis focuses on total water availability from three contributing basins and assesses how drought frequency, duration, and severity may evolve under different emission pathways.

Hydrological modelling was performed using the Soil Moisture Accounting (SMA) method to simulate long-term water balance processes. The historic baseline was simulated for the historical period 1950–2012 and forced with climate projections for 2016–2098 under two scenarios: SSP1-2.6 (low emissions) and SSP5-8.5 (high emissions). To represent climate uncertainty, 10 General Circulation Models downscaled projections for each SSP were initially evaluated, and three were selected using a percentile-based approach. CMCC-ESM2 represents dry conditions (P10), MRI-ESM2-0 represents median conditions (P50), and CanESM5 represents wet conditions (P90). This selection strategy ensures that the modelling framework captures a range of plausible hydroclimatic futures rather than relying on an average projection (Figure 4).



**Figure 4.** Distribution of mean annual precipitation per the General Circulation model.

All models show a moderate increase in annual precipitation for the two SSPs, as shown in Figure 5.



**Figure 5.** Evolution of mean annual precipitation for models CMCC-ESM2 (P10), MRS-ESM2-0 (P50), and CanESM5 (P90).

Drought hazard was quantified using the SDI-12, which is based on accumulated river discharge transformed into standardised anomalies. The index classifies droughts into normal, mild, moderate, severe, and extreme categories, allowing consistent comparison across historical and future periods.

Results show differentiated hazard patterns depending on the climate model and scenario. In the dry model (CMCC-ESM2), the high-emission scenario SSP5-8.5 produces the highest drought frequency but fewer extreme events compared to the historical period. In the median model (MRI-ESM2-0), SSP1-2.6 shows the only occurrence of extreme droughts, while SSP5-8.5 generates longer events. In the wet model (CanESM5), historical conditions present the highest severity, whereas future scenarios generally reduce extreme drought occurrence but modify duration characteristics.

Results seem to indicate low changes in patterns in terms of % of drought periods:

- Historic (13.6 - 16.1)
- SSP1-2.6 (14.0 - 15.2)
- SSP5-8.5 (11.9 - 17.8)

They also seem to indicate a moderate increase in terms of the number of events:

- Historic (20 - 26)
- SSP1-2.6 (25 - 28)
- SSP5-8.5 (24 - 32)

The sum of extreme and severe drought periods seems to be quite stationary, as shown in Figure 6.

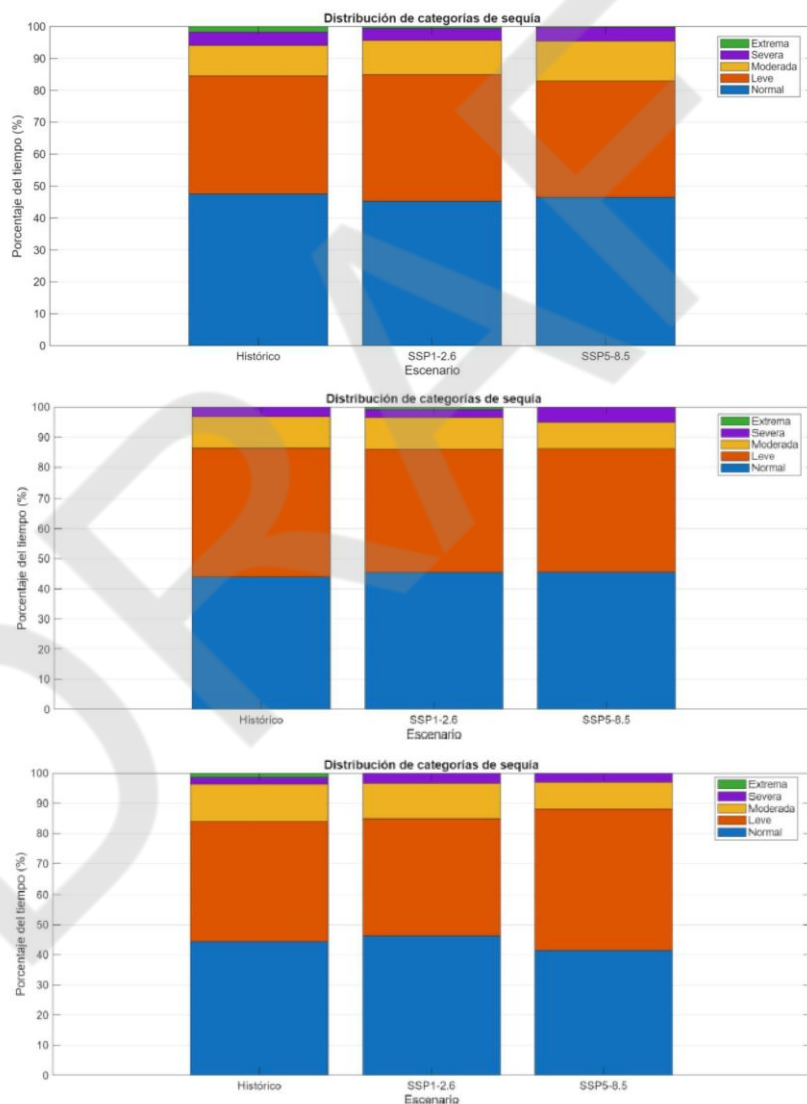


Figure 6. Drought conditions for different models.

So, notwithstanding the moderate increment of the annual precipitation according to the model predictions, rainfall distribution and temperature increase (causing more evapotranspiration losses) provide a framework where drought hazard seems quite stationary with respect to the control historic period.

### Impact assessment results

As shown in Table 5, across all model–scenario combinations, drought conditions represent more than half of the simulated months, ranging from 53.5% to 58.6% of the full time series. This indicates that, under SDI-12, drought is not an exceptional state but a recurrent condition that frequently persists over consecutive months. The highest drought frequency is found for CanESM5–SSP5-5.8 (58.6%), driven primarily by a strong increase in Mild drought months, while the lowest occurs for CMCC–SSP5-8.5 (53.5%).

**Table 5.** Modelling based on SDI-12 (2016–2098). Drought months include Mild, Moderate, Severe and Extreme categories. Percentages refer to the share of total simulated months (N = 985). Climate projections: M2\_ESM2\_0, CMCC\_ESM2 and CanESM5 under SSP1-2.6 and SSP5-8.5.

Model	Projection	Normal months	Drought months	Drought share	Moderate+share (all months)	Severe+share (all months)	Extreme months
M2_ESM2_0	SSP1-2.6	448	537	54.50%	14.00%	3.50%	8
M2_ESM2_0	SSP5-8.5	449	536	54.40%	13.80%	5.10%	0
CMCC_ESM2	SSP1-2.6	446	539	54.70%	15.10%	4.40%	6
CMCC_ESM2	SSP5-8.5	458	527	53.50%	17.10%	4.60%	3
CanESM5	SSP1-2.6	456	529	53.70%	15.30%	3.50%	0
CanESM5	SSP5-8.5	408	577	58.60%	11.80%	3.00%	0

In all cases, the severity profile is clearly dominated by Mild drought, both in absolute terms and conditional on drought occurrence. When expressed as a share of *all months*, Mild drought typically accounts for 36–47% of the period, whereas Moderate-or-worse drought represents approximately 12–17% of all months. Severe-or-worse conditions remain relatively uncommon, generally around 3–5% of the full series, and Extreme drought is rare. These results imply that long-run drought impacts are likely to be driven mainly by the accumulation and persistence of Mild and Moderate events, rather than by frequent extreme outliers.

Differences between SSPs are model-dependent. Under M2\_ESM2\_0, SSP5-8.5 is associated with a strong increase in Severe events (50 vs. 27 under SSP1-2.6). Under CMCC\_ESM2, SSP5-8.5 increases the share of Moderate+ events, indicating an intensification towards more impactful categories. By contrast, CanESM5–SSP5-8.5 increases drought frequency primarily by shifting more months from Normal to Mild, while reducing the relative weight of Moderate conditions.

From the temporal sequence, results indicate longer consecutive sequences of Mild/Moderate drought and intermittent clusters of Severe conditions, particularly in mid-century periods.

Aggregate GDP losses in undiscounted terms range between €52.1 billion and €60.7 billion across model–scenario combinations. The highest loss is estimated for M2\_ESM2\_0–SSP5-8.5 (–€60.7 bn), while the lowest corresponds to CanESM5–SSP1-2.6 (–€52.1 bn). The total spread across scenarios is around €8.6 billion ( $\approx 16\%$ ), indicating moderate but not meaningful inter-model variability (Table 6).

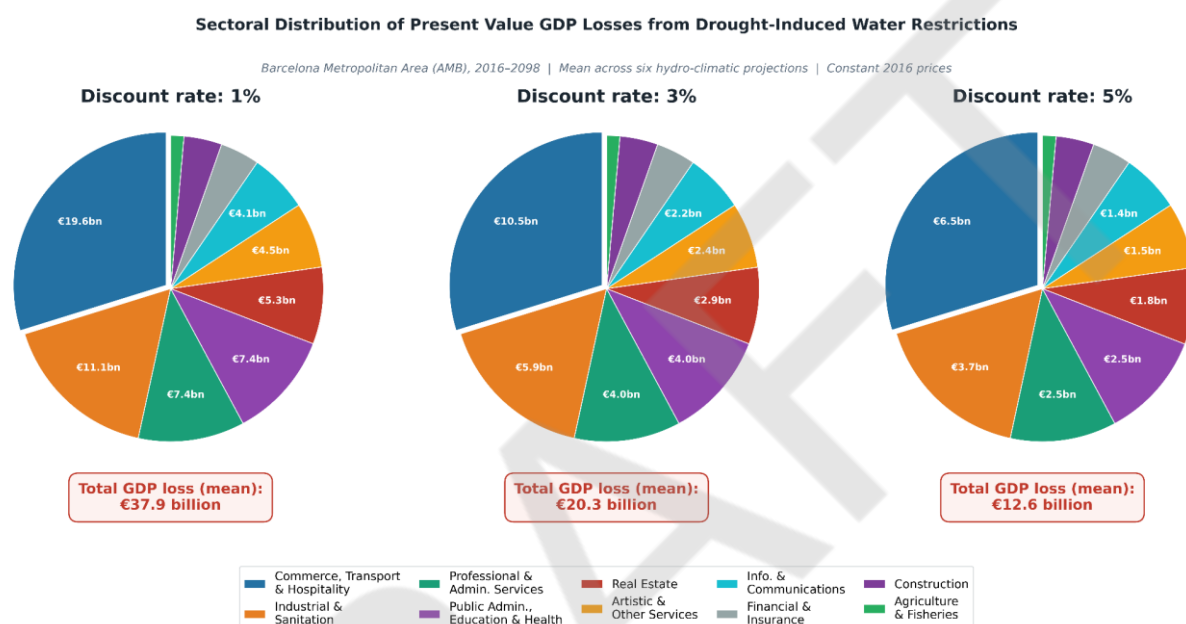
**Table 6.** Undiscounted cumulative economic losses (2016–2098) derived from sector-specific water-demand shocks propagated through the regional Input–Output model. Values expressed in million euros (€m, 2016 prices).

Sectors	M2_ESM2_0		CMCC_ESM2		CanESM5	
	SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5
<b>GDP</b>	-€53,174.04	-€60,696.32	-€57,353.24	-€57,572.44	-€52,139.77	-€53,286.54
<b>Agricultural and Fisheries Products</b>	-€1,323.77	-€1,376.61	-€1,357.59	-€1,338.22	-€1,302.29	-€1,394.44
<b>Industrial and Sanitation Products</b>	-€15,621.06	-€17,507.66	-€16,679.94	-€16,684.64	-€15,327.48	-€15,817.32
<b>Construction Works</b>	-€3,712.37	-€4,262.62	-€4,017.24	-€4,037.18	-€3,639.36	-€3,707.56
<b>Commerce, Transport, and Hospitality Services</b>	-€27,479.72	-€31,542.05	-€29,730.85	-€29,876.43	-€26,939.66	-€27,449.53
<b>Information and Communications Services</b>	-€5,756.59	-€6,625.16	-€6,237.35	-€6,271.09	-€5,642.90	-€5,741.40
<b>Financial and Insurance Services</b>	-€3,830.92	-€4,423.88	-€4,158.66	-€4,183.88	-€3,754.78	-€3,813.26
<b>Real Estate Services</b>	-€7,479.35	-€8,647.76	-€8,124.82	-€8,176.03	-€7,330.36	-€7,439.45
<b>Professional, Scientific, Administrative, and Support Services</b>	-€10,382.94	-€11,964.50	-€11,257.88	-€11,321.49	-€10,177.40	-€10,347.98
<b>Public Administration, Education, and Health Services</b>	-€10,392.43	-€11,972.90	-€11,266.84	-€11,330.05	-€10,186.79	-€10,358.72
<b>Artistic, Entertainment, and Other Services</b>	-€6,465.88	-€7,084.05	-€6,819.17	-€6,791.06	-€6,349.54	-€6,629.29

Discounting substantially reduces the present value of long-term losses. At 1%, PV GDP losses range between €33.2 and €41.4 billion; at 3%, between €15.3 and €24.5 billion; and at 5%, between €8.4 and €16.9 billion. This confirms the strong sensitivity of long-term climate damage valuation to discount rate assumptions.

Across all projections, drought impacts are concentrated in a limited number of highly interconnected sectors. Commerce, Transport and Hospitality consistently record the largest losses (€26.9–€31.5 bn undiscounted), accounting for roughly half of the total GDP shock. Industrial and Sanitation Products represent the second largest impact (€15.3–€17.5 bn), followed by Professional Services and Public Administration ( $\approx$  €10–12 bn each), and Real Estate (€7.3–€8.6 bn). Agriculture and Fisheries show comparatively smaller absolute losses (€1.3–€1.4 bn), reflecting their limited weight within the metropolitan economy. The results, therefore, highlight that drought impacts propagate primarily through service and industrial value chains rather than remaining confined to primary production.

When placed in an economic context, the AMB has a gross metropolitan product of approximately €174 billion (2021). Under a 1% discount rate, drought losses in present value terms (€33–€41 bn) represent approximately 19–24% of one year of current AMB GDP. At 3%, losses (€15–€25 bn) correspond to roughly 9–14% of annual GDP, and at 5% (€8–€17 bn) still represent approximately 5–10%. Even under higher discounting assumptions, cumulative drought impacts therefore constitute a material fraction of the metropolitan economy’s annual output, underscoring the structural relevance of drought risk for long-term economic resilience planning (Figure 7).



**Figure 7.** Sectoral distribution of present value cumulative GDP losses in the AMB, 2016–2098, under alternative discount rates. Values indicate mean sector-level losses across six hydro-climatic projections (MRI-ESM2-0, CMCC-ESM2 and CanESM5 under SSP1-2.6 and SSP5-8.5). Total GDP loss represents the mean aggregate impact. Values in constant 2016 prices.

Overall, the assessment indicates that drought conditions are persistent and recurrent across all projections, with economic losses that are substantial, robust across models, and strongly concentrated in commerce, industry and high-value service sectors. The results confirm the systemic character of drought shocks in a service-oriented metropolitan economy, where indirect propagation effects amplify sectoral water-demand restrictions into significant macroeconomic impacts (Tables 7-9).

**Table 7.** Present value of cumulative drought losses (base year 2016) discounted at 1%. Values in million euros (€m). Discounting reflects the long-term valuation of climate-related economic impacts.

Sector	Present value (2016) at a discount rate of 1%					
	M2_ESM2_0		CMCC_ESM2		CanEMS5	
	SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5
<b>GDP</b>	-€33,215.03	-€41,368.90	-€37,472.71	-€37,408.52	-€38,133.03	-€39,589.69
<b>Agricultural and Fisheries Products</b>	-€842.52	-€938.78	-€899.94	-€877.55	-€940.93	-€1,003.28
<b>Industrial and Sanitation Products</b>	-€9,795.25	-€11,933.97	-€10,929.23	-€10,860.37	-€11,182.25	-€11,672.90

<b>Construction Works</b>	-€2,316.00	-€2,905.18	-€2,622.32	-€2,621.72	-€2,663.84	-€2,760.67
<b>Commerce, Transport, and Hospitality Services</b>	-€17,144.79	-€21,497.50	-€19,408.31	-€19,402.20	-€19,717.62	-€20,436.45
<b>Information and Communications Services</b>	-€3,589.54	-€4,515.31	-€4,070.06	-€4,071.49	-€4,131.64	-€4,278.82
<b>Financial and Insurance Services</b>	-€2,387.04	-€3,015.00	-€2,712.22	-€2,715.49	-€2,750.47	-€2,845.52
<b>Real Estate Services</b>	-€4,659.12	-€5,893.64	-€5,297.87	-€5,305.91	-€5,370.60	-€5,554.07
<b>Professional, Scientific, Administrative, and Support Services</b>	-€6,472.56	-€8,154.23	-€7,344.67	-€7,349.58	-€7,453.02	-€7,715.57
<b>Public Administration, Education, and Health Services</b>	-€6,478.77	-€8,159.97	-€7,350.76	-€7,355.28	-€7,459.67	-€7,722.96
<b>Artistic, Entertainment, and Other Services</b>	-€4,073.39	-€4,829.43	-€4,483.96	-€4,430.29	-€4,618.41	-€4,853.08

**Table 8.** Present value of cumulative drought losses (base year 2016) discounted at 3%. Values in million euros (€m). Discounting reflects the long-term valuation of climate-related economic impacts.

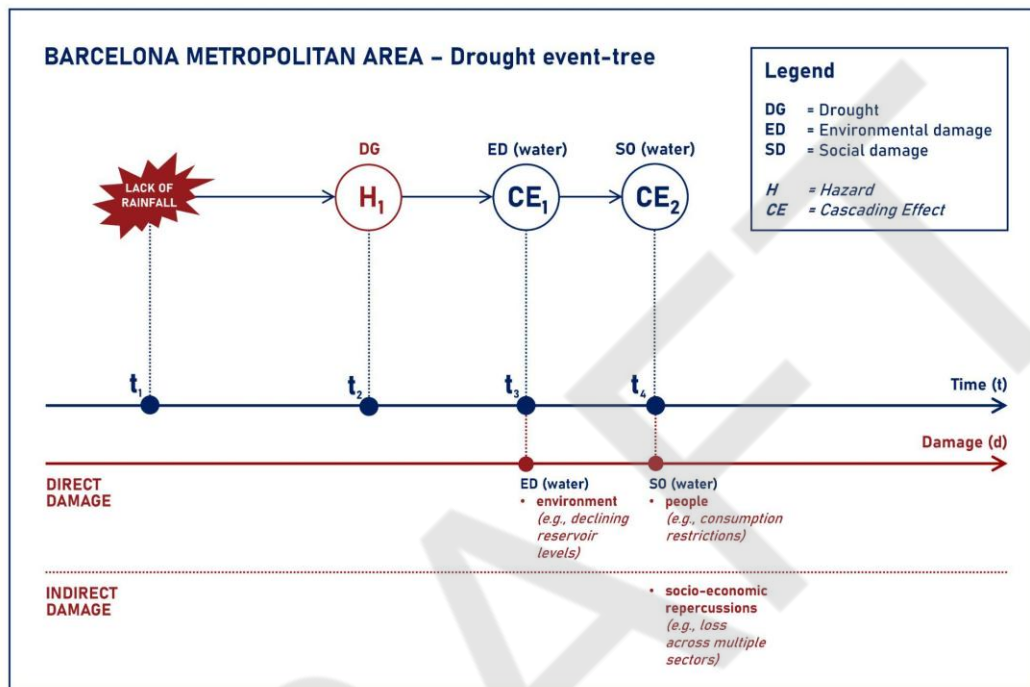
Sector	Present value (2016) at a discount rate of 3%					
	M2_ESM2_0		CMCC_ESM2		CanEMS5	
	SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5
<b>GDP</b>	-€15,251.88	-€22,112.08	-€18,759.72	-€18,268.18	-€22,582.57	-€24,531.56
<b>Agricultural and Fisheries Products</b>	-€400.39	-€505.63	-€465.66	-€440.81	-€556.42	-€595.48
<b>Industrial and Sanitation Products</b>	-€4,530.33	-€6,388.07	-€5,507.81	-€5,333.09	-€6,620.25	-€7,170.05
<b>Construction Works</b>	-€1,060.96	-€1,552.13	-€1,309.97	-€1,278.01	-€1,577.69	-€1,715.52
<b>Commerce, Transport, and Hospitality Services</b>	-€7,855.06	-€11,485.62	-€9,696.57	-€9,458.96	-€11,677.92	-€12,697.45
<b>Information and Communications Services</b>	-€1,642.82	-€2,411.93	-€2,031.47	-€1,983.34	-€2,447.11	-€2,661.92
<b>Financial and Insurance Services</b>	-€1,090.97	-€1,610.09	-€1,352.06	-€1,321.43	-€1,629.15	-€1,773.16
<b>Real Estate Services</b>	-€2,128.31	-€3,147.05	-€2,639.82	-€2,581.03	-€3,181.16	-€3,463.06
<b>Professional, Scientific, Administrative, and Support Services</b>	-€2,960.78	-€4,355.29	-€3,664.23	-€3,578.82	-€4,414.39	-€4,802.89
<b>Public Administration, Education, and Health Services</b>	-€2,963.87	-€4,358.43	-€3,667.55	-€3,581.83	-€4,418.32	-€4,807.00
<b>Artistic, Entertainment, and Other Services</b>	-€1,900.25	-€2,589.86	-€2,278.15	-€2,190.56	-€2,733.27	-€2,949.39

**Table 9.** Present value of cumulative drought losses (base year 2016) discounted at 5%. Values in million euros (€m). Discounting reflects the long-term valuation of climate-related economic impacts.

Sector	Present value (2016) at a discount rate of 5%					
	M2_ESM2_0		CMCC_ESM2		CanEMS5	
	SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5
<b>GDP</b>	-€8,371.4	-€13,597.4	-€11,153.9	-€10,526.4	-€14,863.0	-€16,892.6
<b>Agricultural and Fisheries Products</b>	-€227.1	-€316.6	-€288.4	-€263.5	-€373.3	-€402.7
<b>Industrial and Sanitation Products</b>	-€2,504.3	-€3,941.8	-€3,302.5	-€3,095.8	-€4,374.3	-€4,919.7
<b>Construction Works</b>	-€581.0	-€953.4	-€776.7	-€734.6	-€1,037.0	-€1,182.7
<b>Commerce, Transport, and Hospitality Services</b>	-€4,301.9	-€7,055.5	-€5,750.3	-€5,438.1	-€7,676.7	-€8,753.1
<b>Information and Communications Services</b>	-€898.7	-€1,480.9	-€1,203.2	-€1,139.0	-€1,607.7	-€1,836.0
<b>Financial and Insurance Services</b>	-€596.0	-€987.9	-€799.5	-€757.8	-€1,069.5	-€1,223.8
<b>Real Estate Services</b>	-€1,162.1	-€1,930.6	-€1,560.1	-€1,479.4	-€2,087.9	-€2,390.7
<b>Professional, Scientific, Administrative, and Support Services</b>	-€1,618.9	-€2,673.5	-€2,169.0	-€2,054.2	-€2,899.4	-€3,313.4
<b>Public Administration, Education, and Health Services</b>	-€1,620.8	-€2,675.5	-€2,171.1	-€2,056.1	-€2,902.1	-€3,316.1
<b>Artistic, Entertainment, and Other Services</b>	-€1,059.3	-€1,605.1	-€1,379.9	-€1,283.2	-€1,814.6	-€2,014.8

#### 4.1.2. Drought impact and adaptation: expert-based insights

The drought Mini-trial for the AMB CS is structured around a single-hazard event-tree scenario representing the temporal sequence of processes and impacts associated with prolonged rainfall deficit (Figure 8).



**Figure 8.** Drought event-tree scenario for AMB Mini-trial (replication phase).

The triggering event corresponds to a prolonged lack of rainfall ( $t_1$ ), which initiates drought conditions and progressively reduces available water resources ( $t_2$ ). This causes environmental damage ( $t_3$ ) and social damage ( $t_4$ ), with additional socio-economic losses across multiple sectors, including agriculture, industry, and services ( $t_4$ ). The sequence of events (triggering event, main hazard, and related cascading effects representing further hazard development) shows a slow-onset impact pathway in which impacts materialise gradually after the initial triggering conditions. Impacts include declining reservoir levels and the implementation of water use restrictions.

Within this targeted event-tree scenario, the **ICARIA modelling framework is therefore considered applicable at the regional scale and over temporal horizons ranging from months to years**, in line with the gradual evolution of drought impacts. The modelling process behind drought hazard and impact assessment is based on a **site-specific modelling configuration**, which is calibrated using long-term local datasets, including approximately 50 years of historical rainfall records. Specifically, drought severity is evaluated in accordance with local drought management regulations, which are explicitly tied to the maximum storage capacity and observed water levels of the four main reservoirs supplying the AMB. In this context, the **performance of the ICARIA modelling framework is expected to be highly dependent on the quality and resolution of precipitation and evapotranspiration datasets**. Taken together, all these aspects support the internal coherence and methodological

robustness of the drought modelling workflow, thereby informing **RQ-Sci1** regarding the scientific plausibility and reliability of the modelling results.

From a data requirements and technical constraints perspective, the **effort required to prepare input data for replication is assessed as high**, reflecting the need to adapt the modelling workflow to local data availability and regulatory criteria. Extensive and precise rainfall pattern projections are identified as key factors influencing successful replication in other contexts. The main data-related barriers are associated with fragmented or heterogeneous data sources and limitations in documentation and metadata, which may constrain data harmonisation and integration across contexts. These elements highlight the sensitivity of the modelling configuration to contextual data conditions and calibration requirements, contributing to **RQ-Sci3** by identifying areas where further methodological refinement may be needed, while also informing the technical feasibility dimension of **RQ-Sci2**.

Considering expected outputs, the replication of the drought Mini-trial is anticipated to generate monthly time series of water discharges and water levels for the four reservoirs, directly relevant for monitoring drought evolution and supporting water management decisions under scarcity conditions. No specific adaptation measures are currently modelled within this scenario. According to the experts, the **ICARIA DSS is reported not to support the full modelling workflow required for the drought event-tree scenario** during the replication phase across all modelling components (i.e., 'elementary bricks'). This partial workflow support limits the operational maturity of the system in its current configuration, directly informing **RQ-Sci2** with regard to the practical ease of application, and contributing to **RQ-Sci4** in clarifying the present level of functional integration compared to conventional drought risk/impact assessment approaches.

With respect to replication effort and resource implications, the **main cost drivers** are associated with (i) input data acquisition, harmonisation, and processing, (ii) personnel time required for framework configuration and modelling activities, and (iii) calibration and validation tasks across multiple hazards, exposure/vulnerabilities, risk/impact, and resilience pathways. **The overall cost required to replicate the ICARIA modelling framework is estimated at €20,000–50,000**, with a typical **implementation time of 3-6 months**. The most time-consuming steps include data collection and preparation, cross-scale and cross-dataset harmonisation and preprocessing, parameterisation of framework components, and calibration to local conditions. Two main obstacles are identified as potentially delaying replication or increasing costs: limited availability of adequate datasets and the specific characteristics of the drought and water-resources management context, such as exploitation data of the reservoirs, which influence model calibration requirements and the applicability of regulatory and operational assumptions. These findings provide structured evidence addressing **RQ-Sci2**, particularly in relation to the economic, temporal and organisational feasibility of applying the drought modelling framework in new contexts.

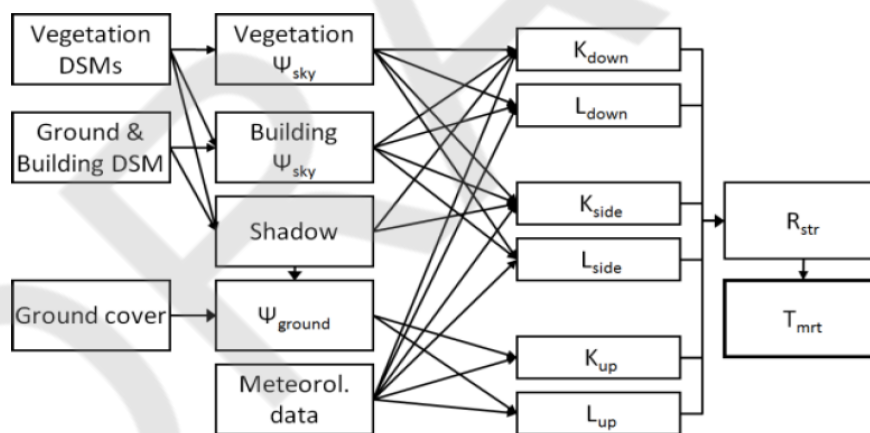
### 4.1.3. Heatwave impact and adaptation: modelling implementation

The objective of this study has focused on analysing the effect of rising temperatures and heatwaves on the Urban Heat Island (UHI) phenomenon in the AMB. Based on these analyses and other relevant information about the territory and population of the AMB, a model has been created for two selected critical assets: EDAR El Prat de Llobregat (a wastewater treatment plant) and Ecoparc Barcelona (a waste management facility).

#### Hazard assessment results

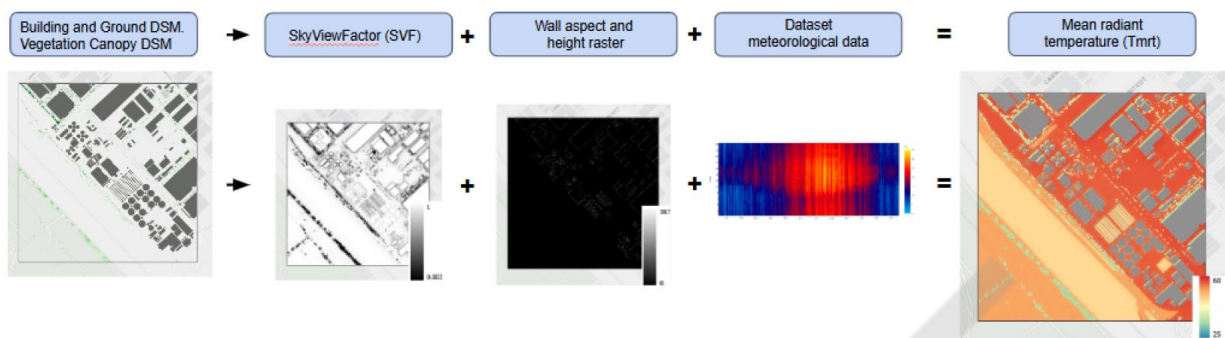
For the development of microclimatic studies of the impact of solar radiation and temperature on environmental health in the identified critical areas of the AMB, the SOLWEIG (Solar and LongWave Environmental Irradiance Geometry) model has been implemented.

SOLWEIG is a model which can be used to estimate spatial variations of 3D radiation fluxes and Mean Radiant Temperature ( $T_{mrt}$ ) in complex urban settings. The SOLWEIG model follows the same approach commonly adopted to observe  $T_{mrt}$ , with shortwave and longwave radiation fluxes from six directions being individually calculated to derive  $T_{mrt}$ . The model requires a limited number of inputs: direct, diffuse and global shortwave radiation, air temperature, relative humidity, urban geometry and geographical information (latitude, longitude and elevation). Additional vegetation and ground cover information can also be used to improve the estimation of  $T_{mrt}$ . A flowchart of the model is shown in Figure 9.



**Figure 9.** SOLWEIG model scheme.

Another mandatory requirement is to have meteorological data (EPW format), as a continuous file or specific momentary values, allowing the selection of long complete periods or periods related to extreme episodes of heatwaves. The following diagram represents a simplified process of implementing the SOLWIEG model (Figure 10).



**Figure 10.** Example of the SOLWEIG model process.

The SOLWEIG model allows studying thermal stress in the city and its influence on human health, by calculating indices such as PET (Physiological Equivalent Temperature) and UTCI (Universal Thermal Comfort Index). These indices will allow us to evaluate the risks derived from heatwaves on human health.

#### Vulnerability calculation

Individuals' metabolic conditions can increase their vulnerability to potential increases in urban temperatures, as excessive heat leads to increased mortality and morbidity. To identify and map vulnerability to high temperatures, a methodology based on the conditions of a typical worker for each work environment in the two study areas has been implemented. Specifically, the following was used as a reference: male, 35 years old, 1.75 m tall, 75 kg in weight, activity level of 80 W, and clothing with a thermal resistance of 0.9.

Three parameters have been defined for a person to be in thermal comfort: the body is in thermal equilibrium, the rate of perspiration is within comfort limits, and the average skin temperature is within comfort limits. These conceptual requirements for determining thermal comfort can be expressed in measurable terms as follows: core body temperature within a very narrow range of 36.5 to 37.5 °C, skin temperature of 30 °C in the extremities and 34 to 35 °C in the trunk and head, and the body is free from perspiration. Any deviation from these parameters produces a feeling of discomfort.

Heat stress results from an imbalance between the demands placed on the worker by the task and the environment, and the worker's capacity to eliminate the heat load modified by clothing.

Heat exchange between the human body and its environment occurs through sensible and latent heat fluxes, radiation, and conduction (generally negligible). Therefore, addressing the thermophysiological assessment of the thermal environment requires the application of a comprehensive heat balance model that considers all heat exchange mechanisms. Input variables include air temperature, water vapour pressure, wind speed, mean radiant temperature (including shortwave and longwave radiation fluxes from the atmosphere), metabolic rate, and clothing insulation.

The PET is an index that provides an estimate of the thermal component of a given environment. The PET is based on the Munich Energy Balance Model for Individuals (MEMI), a two-node model that simulates the thermal conditions of the human body in a physiologically relevant way. It represents

the air temperature at which, in a typical indoor environment (without wind or solar radiation), the thermal balance of the human body equilibrates with the same core and skin temperatures as under the complex outdoor conditions being evaluated (Table 10).

**Table 10.** PET indicator temperature thresholds.

PET (°C)	Thermal sensation	Stress level
>41	Very hot	Extreme heat stress
35 - 41	Hot	Strong heat stress
29 - 35	Warm	Moderate heat stress
23 - 29	Slightly warm	Slight heat stress
18 - 23	Comfortable	No thermal stress
13 - 18	Slightly cool	Slight cold stress
8 - 13	Cool	Moderate cold stress
4 - 8	Cold	Strong cold stress
<4	Very cold	Extreme cold stress

On the other hand, the UTCI is an equivalent temperature (°C) that measures the human physiological response to the thermal environment. It describes the synergistic heat exchanges between the thermal environment and the human body, specifically its energy balance, physiology, and clothing. The UTCI considers how well the population's clothing adapts to the actual ambient temperature. Four variables are required to calculate the UTCI: air temperature at 2 m, dew point temperature at 2 m (or relative humidity), wind speed at 10 m above ground level, and  $T_{mrt}$  (Table 11).

**Table 11.** UTCI indicator temperature thresholds.

UTCI (°C)	Thermal sensation	Stress level
>46	Extreme heat stress	Torrid
38 - 46	Very strong heat stress	Hottish
32 - 38	Strong heat stress	Hot
26 - 32	Moderate heat stress	Warm
9 - 26	No thermal stress	Comfortable
0 - 9	Slight cold stress	Cool
-13 - 0	Moderate cold stress	Coolish
-27 - -13	Strong cold stress	Cold
-40 - -27	Very strong cold stress	Chilly
<-40	Extreme cold stress	Freezing

### Climate horizons

The following scenarios, developed by the Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment Report (AR6) (IPCC, 2023), have been taken into account:

- SSP1-2.6: This scenario, with 2.6 W/m<sup>2</sup> by 2100, is a modified version of the optimistic RCP2.6 scenario and was designed to simulate development compatible with the 2°C target. This scenario also assumes the adoption of climate protection measures. Effects of heat island episodes for events within the time horizons 2015 to 2040, 2040 to 2070, and 2070 to 2100.

- SSP5-8.5: With an additional radiative forcing of 8.5 W/m<sup>2</sup> by the year 2100, this scenario represents the upper limit of the range of scenarios described in the literature. It can be understood as an update of the CMIP5 RCP8.5 scenario, now combined with socio-economic factors. Effects of heat island episodes for events within the time horizons 2015 to 2040, 2040 to 2070, and 2070 to 2100.

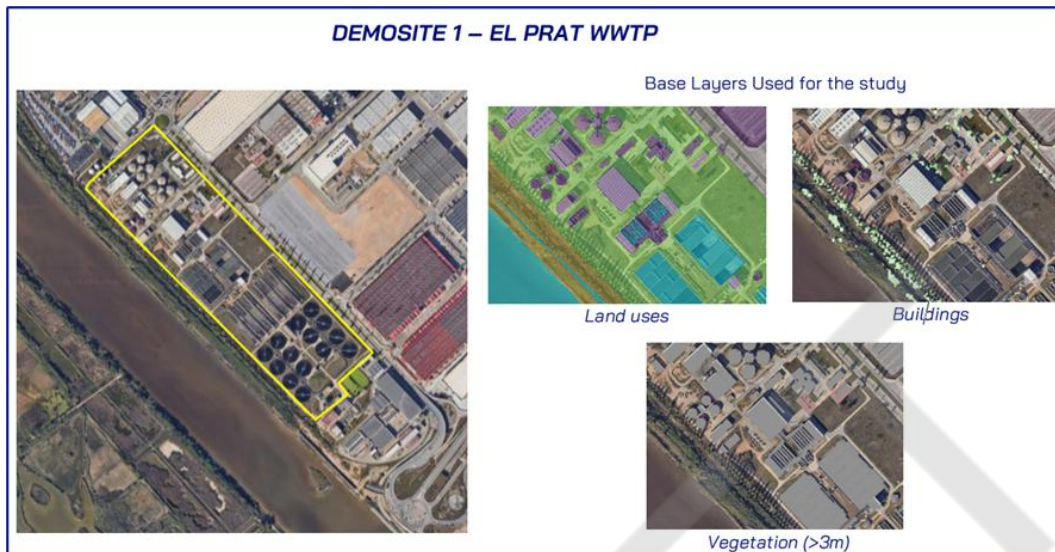
To calculate the indicators for the different time horizons, the EPW meteorological files have been modified to apply the possible future climate conditions to the model, as well as the potential percentiles within each scenario (90th and 50th percentiles). The result is a file modified to reflect future climate conditions for the years 2040, 2070, and 2100, along with their corresponding 50th and 90th percentiles (Figure 11).



**Figure 11.** Change in radiation (W/m<sup>2</sup>) for different horizons and percentiles in the study area.

[Risk assessment of the heat island hazard model for the AMB - DEMOSITE 1 \(EDAR El Prat de Llobregat\)](#)

The Wastewater Treatment Plant (WWTP) is located in the municipality of El Prat de Llobregat, in the delta of the Llobregat River, and treats the water of the Baix Llobregat sanitation system. In addition, the treatment plant includes a water regeneration station (Figure 12).



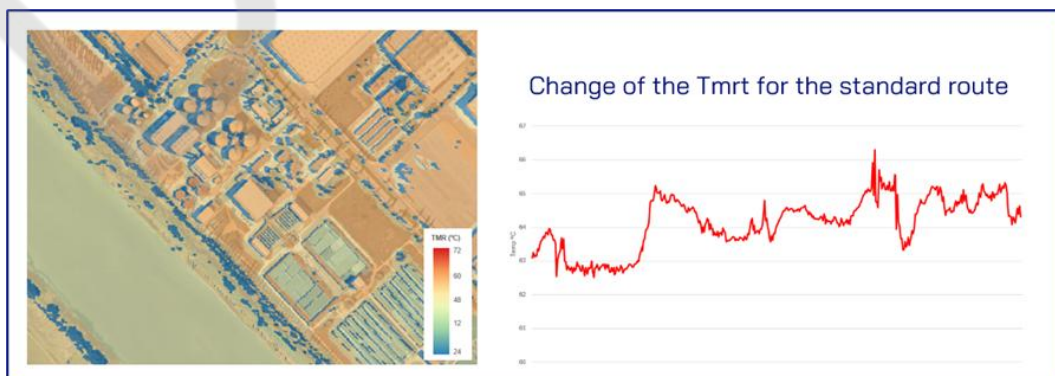
**Figure 12.** Contextualization of El Prat de Llobregat WWTP.

Exposure is established through the calculation of the Tmrt. To analyse the Tmrt, 3 study points and a typical route with the presence of workers throughout a working day have been chosen (Figure 13).



**Figure 13.** Study points chosen and the typical workers' route.

As a result, a heat map is obtained with the Tmrt in the study area and the change of the Tmrt by the standard route for 08/23/23 at 12:00 pm (Figure 14).



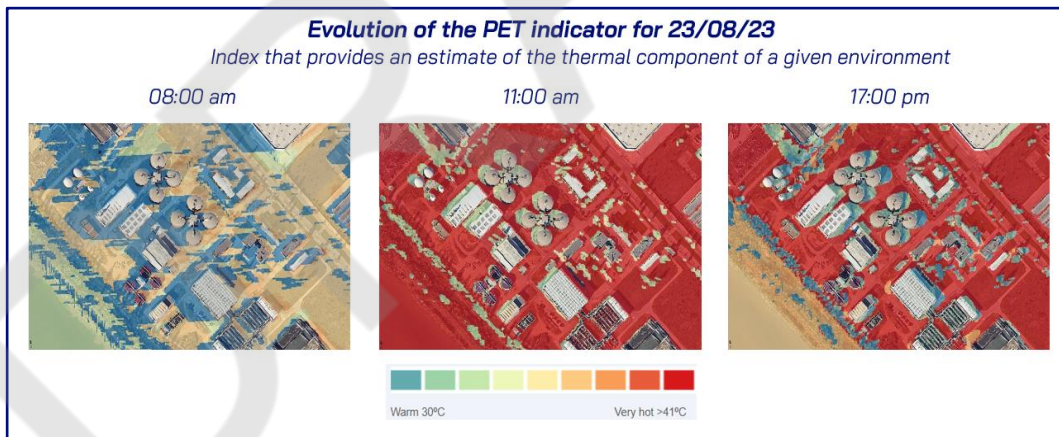
**Figure 14.** Change of the Tmrt for the standard route.

Vulnerability is assessed as the risks to human health from heatwaves. Heat stress results from the imbalance between the demands placed on the worker by the task and the environment, and the worker's ability to remove the modified heat load from clothing. Figure 15 shows the evolution of the Tmrt for 23/08/23 during a typical working day from 8 am to 7 pm.

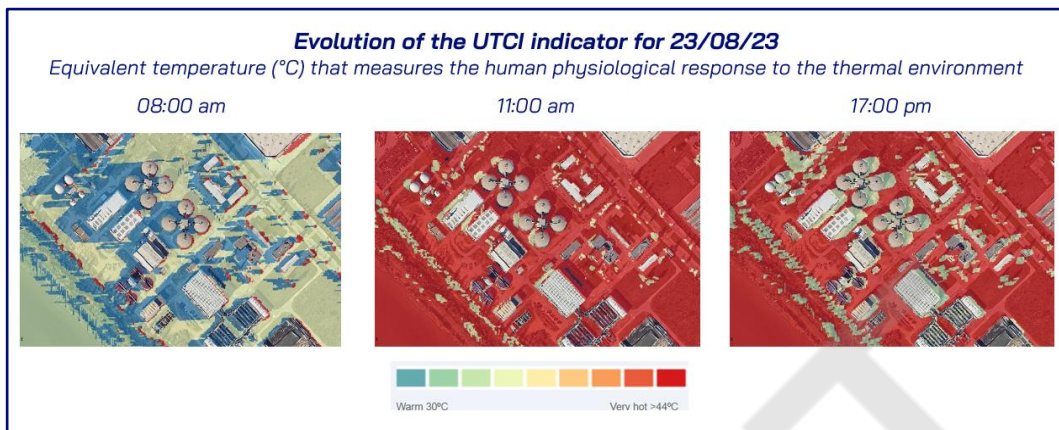


**Figure 15.** Evolution of the Tmrt.

To identify and map vulnerability to high temperatures, a methodology is implemented based on the conditions of a typical worker for each work environment in the two areas of study (man, 35 years old, 1.75 m tall, 75 kg weight, 80 W activity and clothing with thermal resistance of 0.9 clo). The PET (Figure 16) and the UTCI (Figure 17) are calculated to assess heat stress and its influence on human health.



**Figure 16.** Evolution of the PET indicator.



**Figure 17.** Evolution of the UTCI indicator.

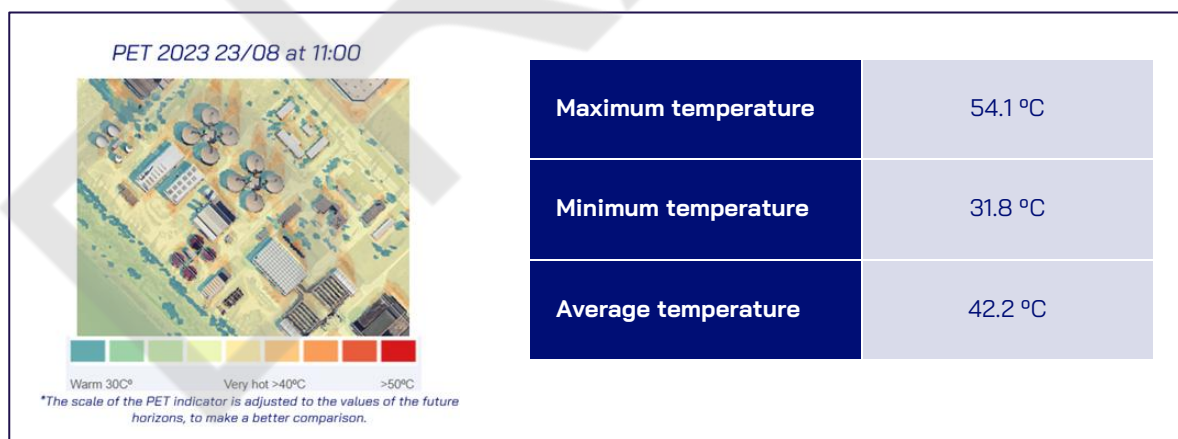
Impact assessment results

The PET and UTCI indicators are analysed for the different scenarios developed by the IPCC's AR6 (IPCC, 2023) report in the face of possible warming scenarios (Figure 18).



**Figure 18.** Analysed scenarios.

Based on the base scenario of August 23, 2023, at 11:00 am, below are the results of the PET indicator for the two climate scenarios SSP1-2.6 and SSP5-8.5, in their respective horizons and percentiles (Figures 19-27).

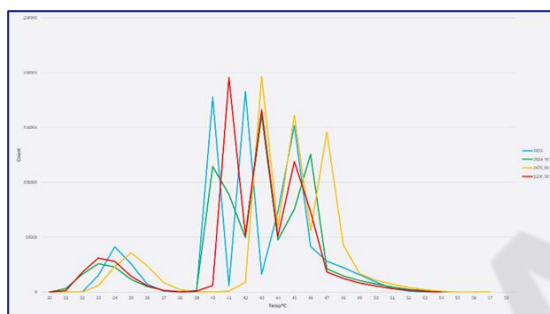


**Figure 19.** PER 23/08 11:00 am.

Scenario 1-2.6:



**Figure 20.** Evolution of the PET indicator for the horizon 1-2.6 p50 for the day 23/08 at 11:00 am.



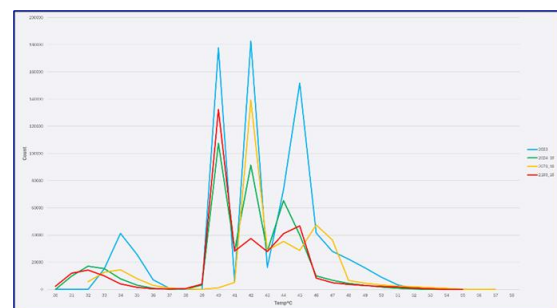
**Figure 21.** Pixels of high Tmrt for each projection.

The graph (Figure 21) represents the total number of pixels with a temperature value. An increase in the number of pixels with higher temperature values is observed over the years, exceeding the maximum temperature of 2023 from 54.1°C to 55.2°C in 2070. It is worth highlighting the year 2027 as the horizon with the highest temperature values, exceeding the values of the 2100 horizon.



**Figure 22.** Evolution of the PET indicator for the horizon 1-2.6 p90 for the day 23/08 at 11:00 am.

The graph (Figure 23) represents the total number of pixels with a temperature value. An increase in the number of pixels with higher temperature values is observed over the years, exceeding the maximum temperature of 2023 from 54.1°C to 56.6°C in 2070. It is worth highlighting the year 2027 as the horizon with the highest temperature values, exceeding the values of the 2100 horizon.



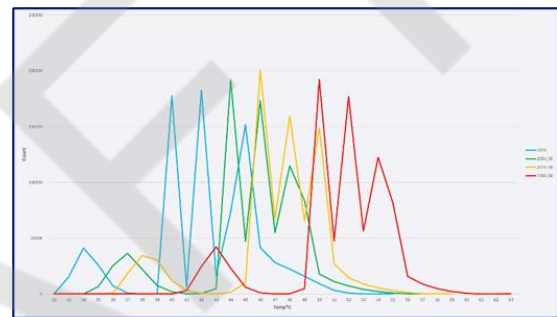
**Figure 23.** Pixels of high Tmrt for each projection.

Scenario 585:



**Figure 24.** Evolution of the PET indicator for the horizon 5-8.5 p50 for the day 23/08 at 11:00 am.

The graph (Figure 25) represents the total number of pixels with a temperature value. An increase in the number of pixels with higher temperature values is observed as the years progress. The maximum temperature of 2023 is exceeded from 54.1°C to 61°C in the year 2100. Unlike in scenario 126, for scenario 5-8.5, the year 2100 stands out as the horizon with the highest temperature values.

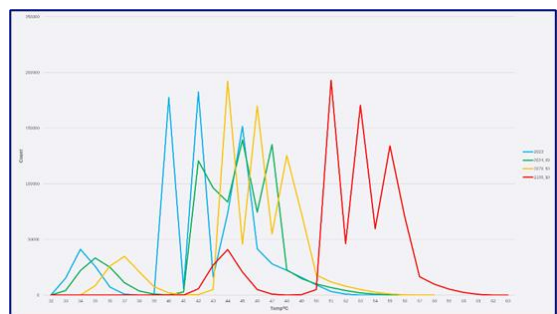


**Figure 25.** Pixels of high Tmrt for each projection.



**Figure 26.** Evolution of the PET indicator for the horizon 5-8.5 p90 for the day 23/08 at 11:00 am.

The graph (Figure 27) represents the total number of pixels with a temperature value. An increase in the number of pixels with higher temperature values is observed as the years progress. The maximum temperature of 2023 is exceeded from 54.1°C to 61.9°C in the year 2100. The year 2100 stands out with temperatures much higher than the base scenario and the coming years, reaching an average temperature of 52.2°C, 10°C more than the average temperature of 2023.



**Figure 27.** Pixels of high Tmrt for each projection.

Table 12 presents a summary of all indicators and horizons for the EDAR\_1.

**Table 12.** Analysis of the different indicators and horizons for the study point **edar\_1** at **11:00 am** on **08/23**.

SSP	Event intensity percentile	Projection period	Tmrt (°C)	PET (°C)	UTCI (°C)
Historic	-	2023	33.81	31.79	33.13
		2015-2040	60.28	42.02	41.22
1-2.6	50	2041-2070	61.16	42.82	41.65
		2071-2100	59.58	41.06	40.22
		2015-2040	60.44	42.98	41.78
	90	2041-2070	61.66	43.36	42.09
		2071-2100	60.25	41.35	40.86
		2015-2040	61.45	43.24	41.79
5-8.5	50	2041-2070	61.87	43.84	42.94
		2071-2100	65.20	50.64	47.63
		2015-2040	61.97	44.50	42.82
	90	2041-2070	62.42	44.59	43.84
		2071-2100	66.47	51.78	48.54
		2015-2040	61.45	43.24	41.79

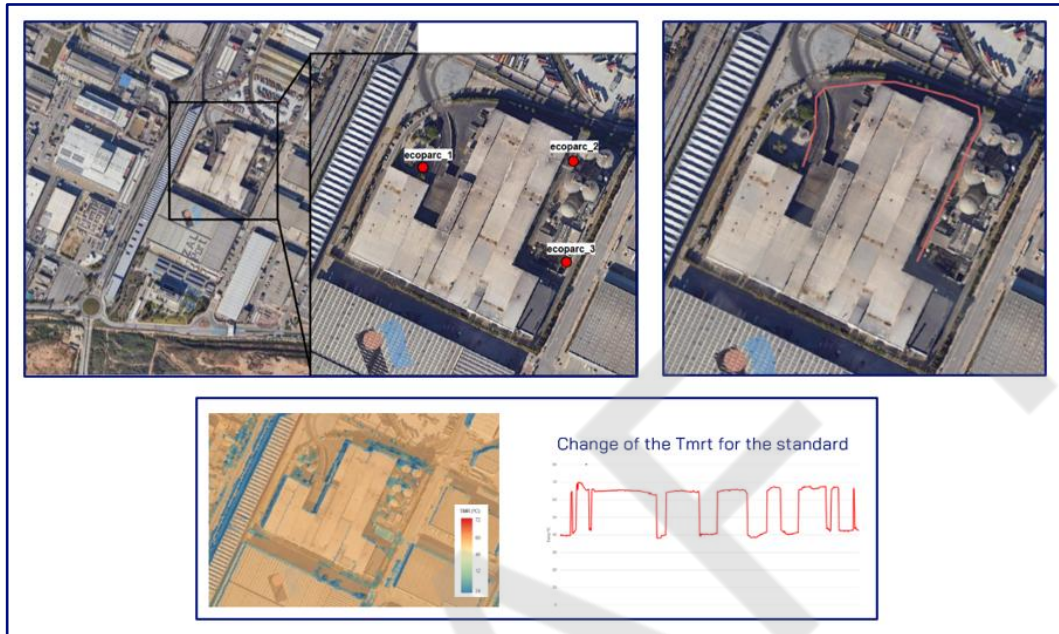
Risk assessment of the heat island hazard model to the AMB - DEMOSITE 2 (Ecoparc 1)

Ecoparc Barcelona is located in the municipality of Prat de Llobregat, in the delta of the Llobregat River. It is environmental equipment for the comprehensive treatment of AMB waste. Its function is to valorise the organic fraction and the rest through various complementary treatments (Figure 28).



**Figure 28.** Contextualization of Ecoparc 1.

To analyse the Tmrt, 3 study points and a typical route where there is the presence of workers throughout a working day have been chosen. As a result, a heat map has been obtained with the Tmrt in the study area and the change of the Tmrt by the standard route for 08/23/23 at 12:00 pm (Figure 29).



**Figure 29.** Study points chosen, typical workers' route and evolution of Tmrt.

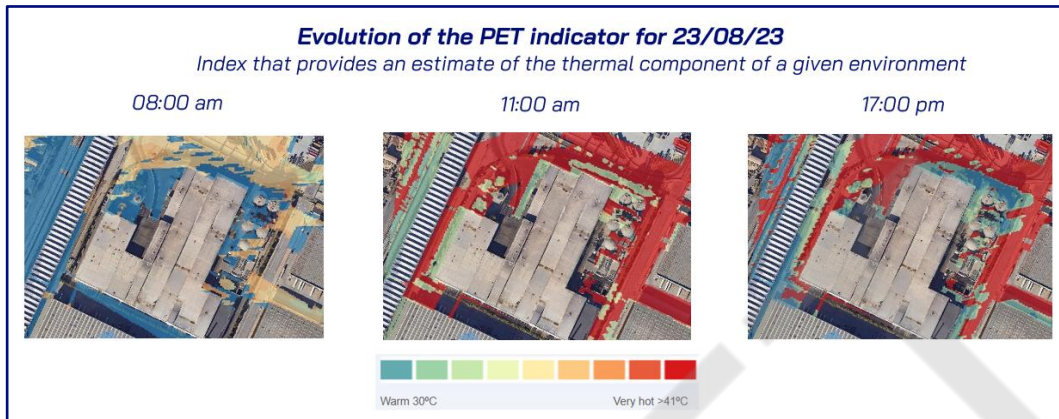
Heat stress results from the imbalance between the demands placed on the worker by the task and the environment, and the worker's ability to remove the modified heat load from clothing. Figure 30 shows the evolution of the Tmrt for 23/08/23 during a typical working day from 8 am to 7 pm.



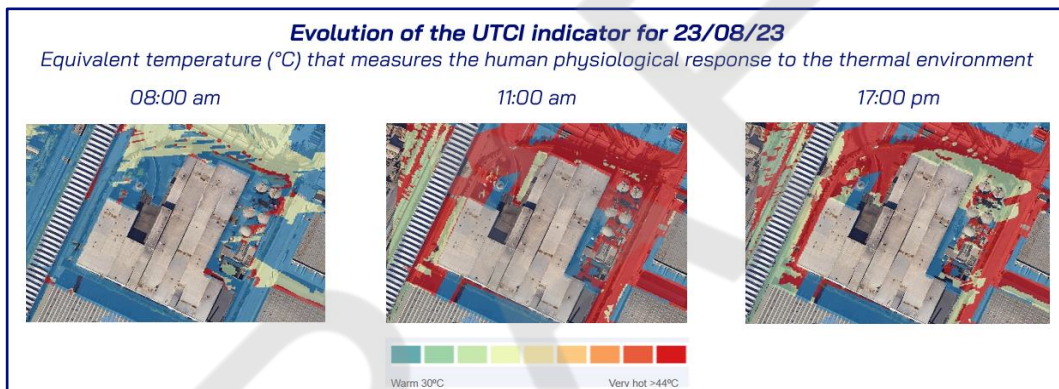
**Figure 30.** Evolution of the Tmrt.

To identify and map vulnerability to high temperatures, a methodology has been implemented based on the conditions of a typical worker for each work environment in the two areas of study (man, 35 years old, 1.75 m tall, 75 kg weight, 80 W activity and clothing with thermal resistance of 0.9 clo). The

PET (Figure 31) and the UTCI (Figure 32) are calculated to assess heat stress and its influence on human health.



**Figure 31.** Evolution of the PET indicator.



**Figure 32.** Evolution of the UTCI indicator.

Impact assessment results

The PET and UTCI indicators are analysed for the different scenarios developed by the sixth IPCC report in the face of possible warming scenarios (Figure 33).



**Figure 33.** Analysed scenarios.

Based on the base scenario of August 23, 2023, at 11:00 pm., below are the results of the PET indicator for the two climate scenarios SSP1-2.6 and SSP5-8.5, in their respective horizons and percentiles (Figures 34-42).

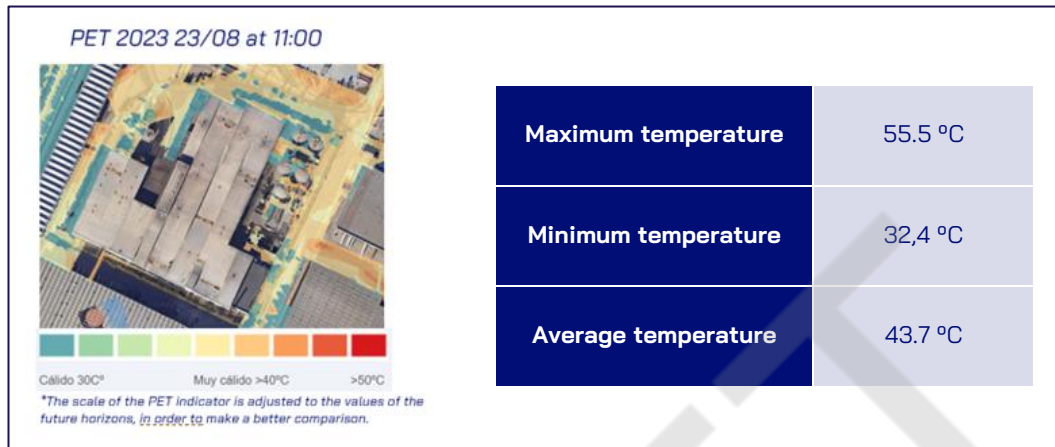


Figure 34. PET 23/08 11:00 am.

Scenario 126:

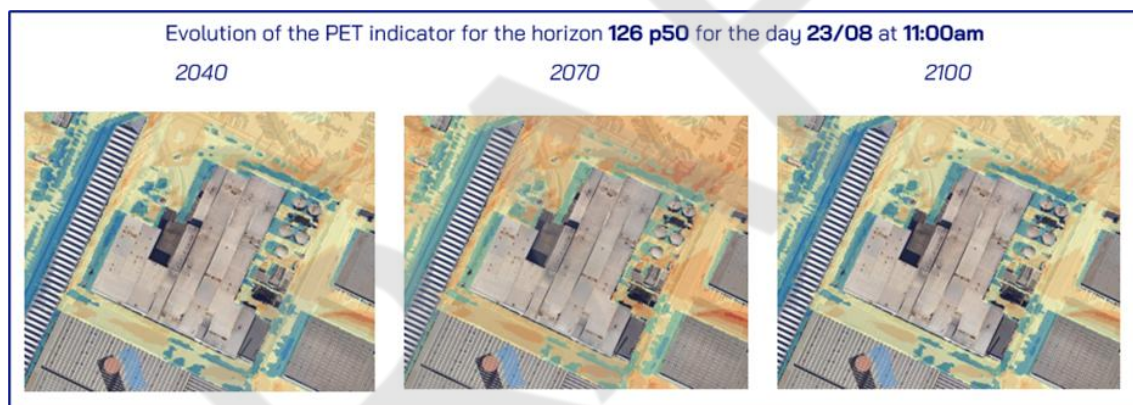


Figure 35. Evolution of the PET indicator for the horizon 1-2.6 p50 for the day 23/08 at 11:00 am.

The graph (Figure 36) represents the total number of pixels with a temperature value. An increase in the number of pixels with higher temperature values is observed over the years, exceeding the maximum temperature of 2023 from 55.5°C to 56.6°C in 2070. It is worth highlighting the year 2027 as the horizon with the highest values of high temperatures, exceeding the values of the 2100 horizon.

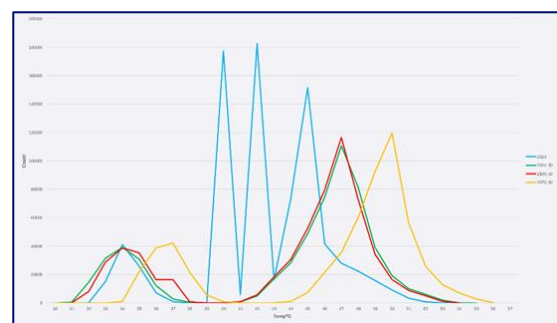
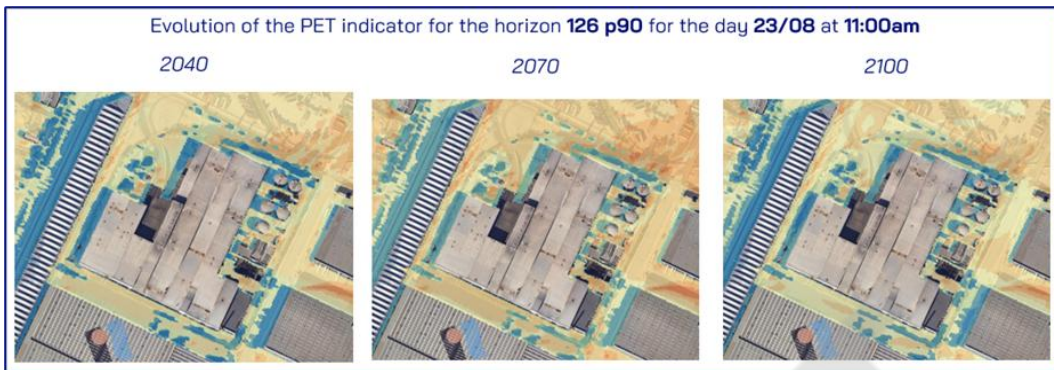
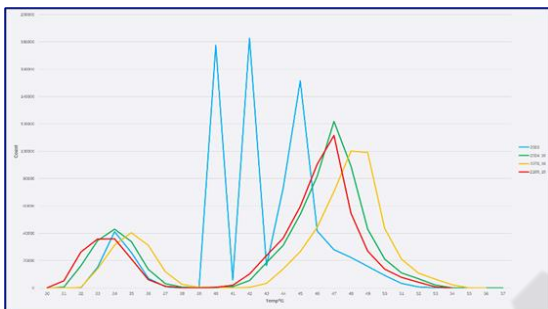


Figure 36. Pixels of high Tmrt for each projection.



**Figure 37.** Evolution of the PET indicator for the horizon 1-2.6 p90 for the day 23/08 at 11:00 am.



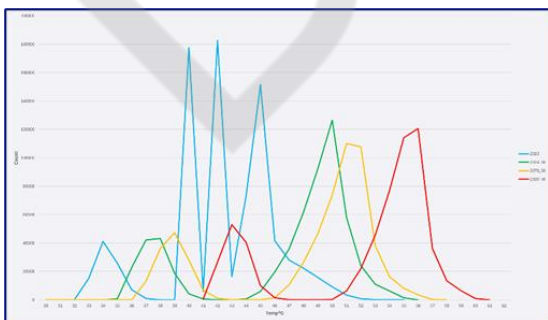
**Figure 38.** Pixels of high Tmrt for each projection.

The graph (Figure 38) represents the total number of pixels with a temperature value. An increase in the number of pixels with higher temperature values is observed over the years, exceeding the maximum temperature of 2023 from 55.5°C to 56.0°C in 2070. It is worth highlighting the year 2027 as the horizon with the highest temperature values, exceeding the values of the 2100 horizon.

Scenario 585:



**Figure 39.** Evolution of the PET indicator for the horizon 5-8.5 p50 for the day 23/08 at 11:00 am.



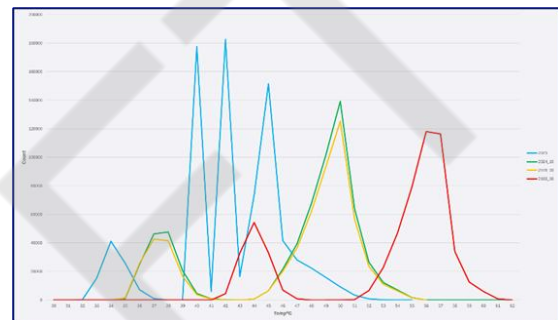
**Figure 40.** Pixels of high Tmrt for each projection.

The graph (Figure 40) represents the total number of pixels with a temperature value. An increase in the number of pixels with higher temperature values is observed as the years progress. The maximum temperature of 2023 is exceeded from 55.5°C to 60.8°C in the year 2100. Unlike in scenario 1-2.6, for scenario 5-8.5, the year 2100 stands out as the horizon with the highest temperature values (Figure 41).



**Figure 41.** Evolution of the PET indicator for the horizon 5-8.5 p90 for the day 23/08 at 11:00 am.

The graph (Figure 42) represents the total number of pixels with a temperature value. An increase in the number of pixels with higher temperature values is observed as the years progress. The maximum temperature of 2023 is exceeded from 54.1°C to 61.7°C in the year 2100. The year 2100 stands out with temperatures much higher than the base scenario and the coming years, reaching an average temperature of 53.2°C, 9.5°C more than the average temperature of 2023.



**Figure 42.** Pixels of high Tmrt for each projection.

Table 13 presents a summary of all indicators and horizons for the Ecoparc\_2.

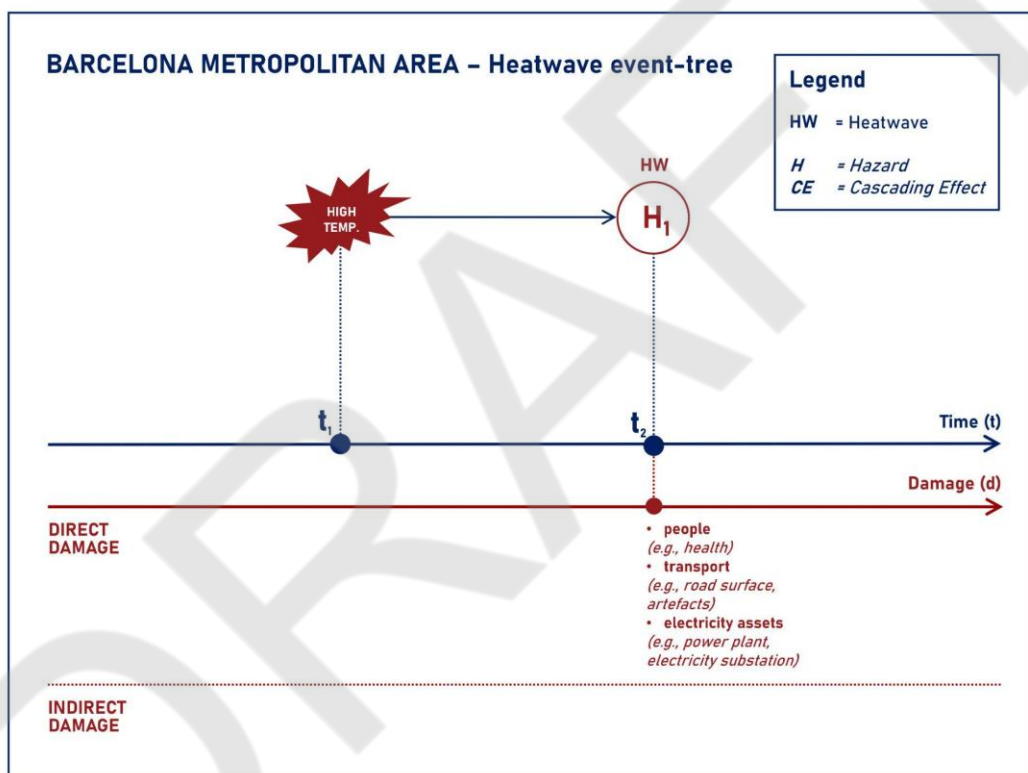
**Table 13.** Analysis of the different indicators and horizons for the study point **ecoparc\_2** at **11:00 am** on **08/23**.

SSP	Event intensity percentile	Projection period	Tmrt (°C)	PET (°C)	UTCI (°C)
Historic	-	2023	38,22	34,81	35,22
		2015-2040	40,02	33,04	37,03
1-2.6	50	2041-2070	40,95	34,09	37,63
		2071-2100	40,14	32,47	36,13
		2015-2040	40,40	34,66	38,05
		2041-2070	42,19	35,75	38,66
1-2.6	90	2071-2100	40,63	33,30	37,11
		2015-2040	41,32	36,70	38,13
		2041-2070	42,61	39,38	39,35
5-8.5	50	2015-2040	41,32	36,70	38,13
5-8.5	50	2041-2070	42,61	39,38	39,35

	90	2071-2100	47,41	42,71	43,94
		2015-2040	42,66	37,67	39,24
		2041-2070	43,85	38,18	40,21
		2071-2100	48,14	43,52	44,67

#### 4.1.4. Heatwave impact and adaptation: expert-based insights

The heatwave Mini-trial for the AMB CS is structured around a single-hazard event-tree scenario representing the temporal sequence of processes and impacts associated with extreme heat (Figure 43).



**Figure 43.** Heatwave event-tree scenario for AMB Mini-trial (replication phase).

The triggering event corresponds to a sustained increase in air temperature ( $t_1$ ), which progressively evolves into a heatwave event ( $t_2$ ). Once heatwave conditions are established, elevated temperatures intensify thermal stress within the urban environment through the amplification of the urban heat island effect, particularly in densely built-up and populated areas, causing direct short-term damage to people, transport, and electricity assets ( $t_2$ ). The sequence of events (triggering event and main hazard) reflects a rapid-onset impact pathway in which impacts materialise shortly after the initial triggering conditions. Impacts include adverse effects on human health, especially among vulnerable population groups, as well as degradation and/or malfunctioning of the transport network (e.g., road

surface, artefacts, etc.) and the electricity network (e.g., power plant, electricity substation, etc.), with limited cascading effects beyond immediate heat-related stress mechanisms.

Within this targeted event-tree scenario, the **ICARIA modelling framework is considered applicable primarily at the local scale and over temporal horizons ranging from hours to days**. The modelling process underlying heatwave hazard and impact assessment relies on a configuration requiring detailed and accurate information on buildings and urban surfaces. In particular, the evaluation of the urban heat island effect is based on the SOLWEIG model, which assesses thermal stress at the scale of individual buildings or urban areas. In this context, the **performance of the ICARIA modelling framework is expected to be largely dependent on the quality and resolution of structural and urban morphology datasets**. Taken together, all these aspects support the internal coherence and methodological robustness of the heatwave modelling workflow, thereby informing **RQ-Sci1** regarding the scientific plausibility and reliability of the modelling results.

From a data requirements and technical constraints perspective, the **effort required to prepare input data for replication is considered moderate**, as it relies on accurate structural and morphological information to characterise heat interactions within the urban environment. Urban pattern data are, therefore, key factors influencing successful replication in other urban contexts. The main data-related barriers are associated with restricted or proprietary access to building-related information and with fragmented or heterogeneous data sources, which may constrain harmonisation and integration across contexts. These elements highlight the sensitivity of the modelling configuration to contextual data conditions and calibration requirements, contributing to **RQ-Sci3** by identifying areas where further methodological refinement may be needed, while also informing the technical feasibility dimension of **RQ-Sci2**.

Considering expected outputs, the replication of the heatwave Mini-trial is anticipated to generate high-resolution surface heat maps representing temperature distributions at square-metre (m<sup>2</sup>) spatial resolution and hourly temporal resolution. These outputs are regarded as directly relevant for identifying urban hot spots and supporting targeted heatwave risk/impact management measures, particularly in relation to urban planning and design decisions. No specific adaptation measures are currently modelled within this scenario. The expert indicates that the **ICARIA DSS does not support the full modelling workflow required for the heatwave event-tree scenario** during the replication phase across all modelling components (“elementary bricks”). This partial workflow support limits the operational maturity of the system in its current configuration, directly informing **RQ-Sci2** with regard to the practical ease of application, and contributing to **RQ-Sci4** by clarifying the present level of functional integration compared to conventional urban heatwave risk/impact assessment approaches.

Main cost drivers with respect to replication effort and resource implications are associated with (i) input data acquisition, harmonisation, and processing, (ii) personnel time required for framework configuration and modelling activities, and (iii) calibration and validation tasks across multiple hazards, exposure/vulnerabilities, risk/impact, and resilience pathways. **The overall cost required to replicate the ICARIA modelling framework is estimated at €10,000–20,000, with a typical implementation time of 1-3 months**. The most time-consuming steps include data collection and preparation, as well as cross-scale and cross-dataset harmonisation and preprocessing. The principal

obstacle identified as potentially delaying replication or increasing costs is the availability of accurate building structure information for large urban areas. These findings provide structured evidence addressing **RQ-Sci2**, particularly in relation to the economic, temporal, and organisational feasibility of applying the heatwave modelling workflow in new contexts.

#### 4.1.5. Wildfire impact and adaptation: modelling implementation

##### Risk assessment methodology

The risk assessment for wildfires on natural areas in the AMB was done through the DSS created by DRAXIS and CERTH, and the methodology proposed by DEMOKRITOS in the D4.2 (de la Cruz Coronas et al., 2026). The analysis is based on SSP1-2.6 and SSP5-8.5 to allow a comparison between the most optimistic and most pessimistic future directions. Four different periods of time (historic, 2015-2040, 2041-2070 and 2071-2100) were studied to include in the analysis the development of risk through future projections.

The DSS methodology involves the creation of hazard and exposure data in shapefile format (.shp). Hazard data is presented as a vector layer containing information on the Fire Weather Index (FWI) for each of the pixels in the area. Specifically, each cell includes information on the number of days that FWI surpasses level 50 annually. Exposure data is provided with the Corine Land Cover land uses, also in a vector layer. The exposure information is also used by the tool to establish the area being assessed. The DSS allows users to upload the layer itself or to provide coordinates and download the data of the Corine Land Cover automatically from the EU Copernicus service. Once this information is uploaded onto the platform, the risk assessment process is carried out and results in new data representing risk and vulnerability within the area considered.

##### Hazard assessment results

Climate data for hazard assessment of the AMB was provided by the FIC. FWI was the chosen indicator for evaluating the probability of extreme wildfires developing once started. The FWI compiles conditions of humidity of the different floor layers, temperature and wind in order to estimate the evolution of fires. The hazard is divided into six levels: Very low (FWI <5.2), Low (FWI 5.2-11.2), Moderate (FWI 11.2-21.3), High (FWI 21.3-38.0), Very high (FWI 38.0-50.0), Extreme (FWI >50.0).

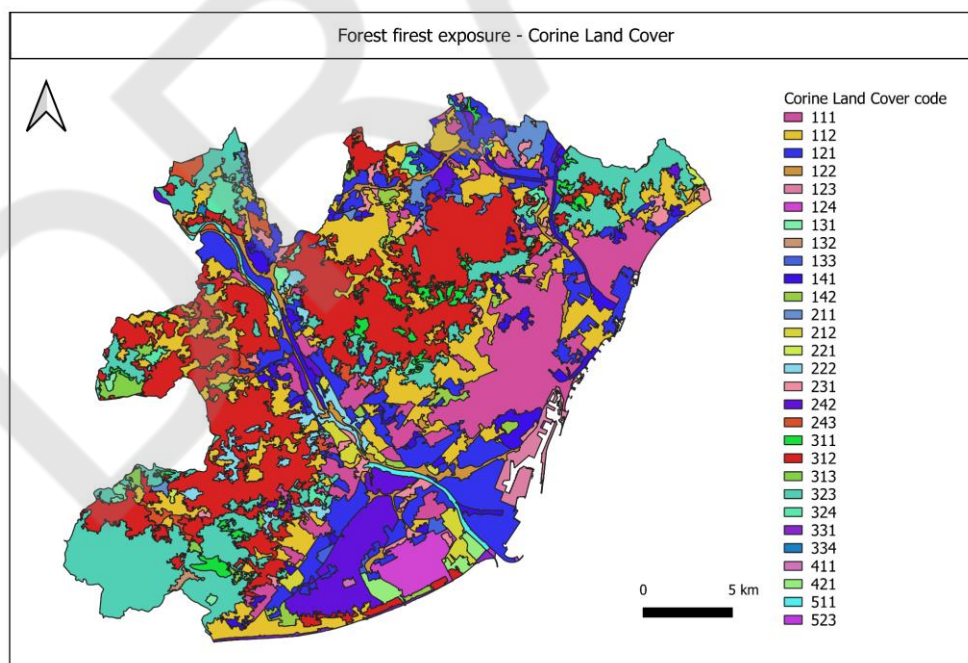
For the AMB, the projections show little increment of FWI for the different projections compared to historical data. The mean FWI was then translated to FWI>38. The “Very high” hazard level was chosen instead of the “Extreme” level for this analysis, as hazard levels don’t exceed a level of 50 FWI for any of the projections studied. For the most pessimistic scenarios, the number of days with FWI>38 is 7.5 in the historic period, and increases around 2-3 days for future projections, with a maximum increase of 6 days by 2100. The number of days with FWI>38 is used by the DSS to set a level of hazard from 1 to 5. For the AMB, this means a hazard level of 1 throughout the whole area, as shown in Figure 44.



**Figure 44.** Hazard map for wildfires in the AMB created with the DSS.

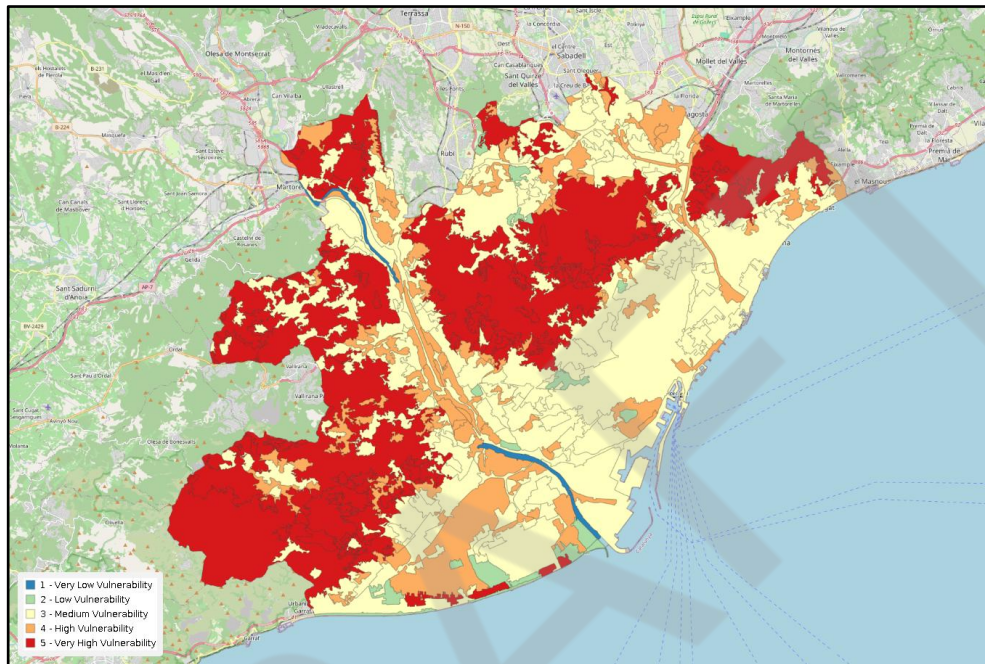
Exposure and vulnerability assessment

As mentioned above, exposure is obtained through the Corine Land Cover (Figure 45). This data offers standard information on the different types of land used in the area studied. The areas within the AMB include artificial surfaces, agricultural areas, forest and seminatural areas, wetlands and water bodies.



**Figure 45.** Corine Land Cover map of the AMB.

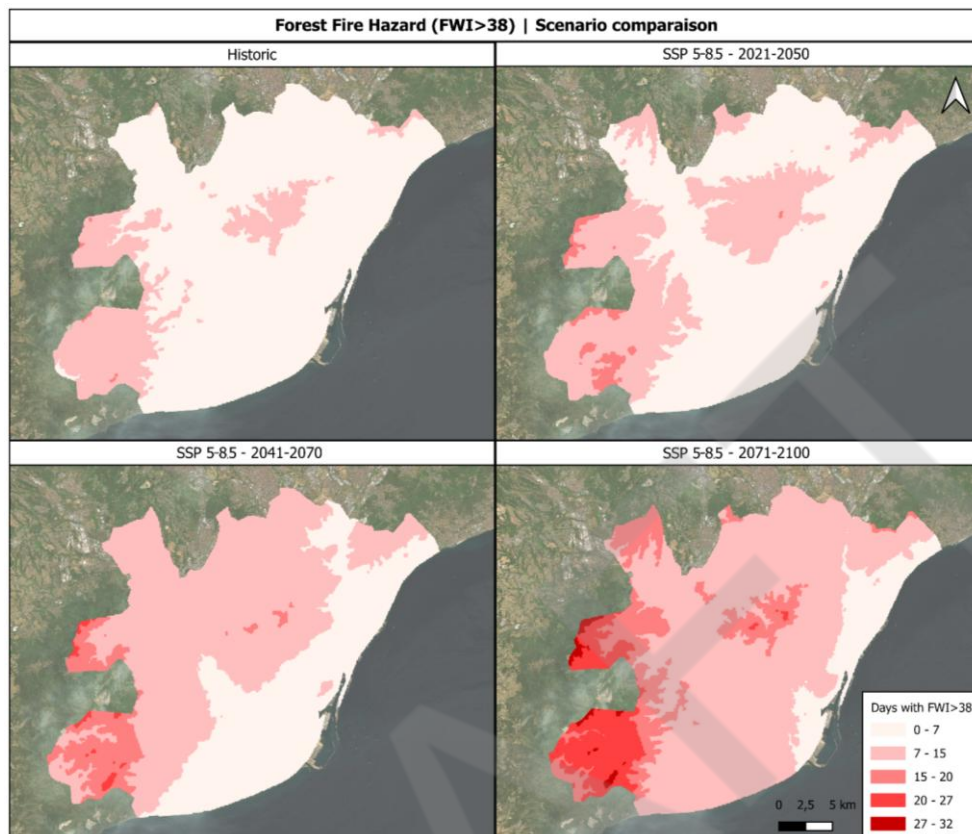
The DSS tool takes this information and, depending on the Corine Land Cover code, assigns a vulnerability value from 1 to 5. Forest and agricultural areas are considered as high vulnerability areas, wetlands and water bodies are considered as very low vulnerability areas and artificial areas are considered as medium or high vulnerability areas. The results of this analysis are transformed into a map shown in Figure 46.



**Figure 46.** Vulnerability map of the AMB created with the DSS.

### Impact assessment results

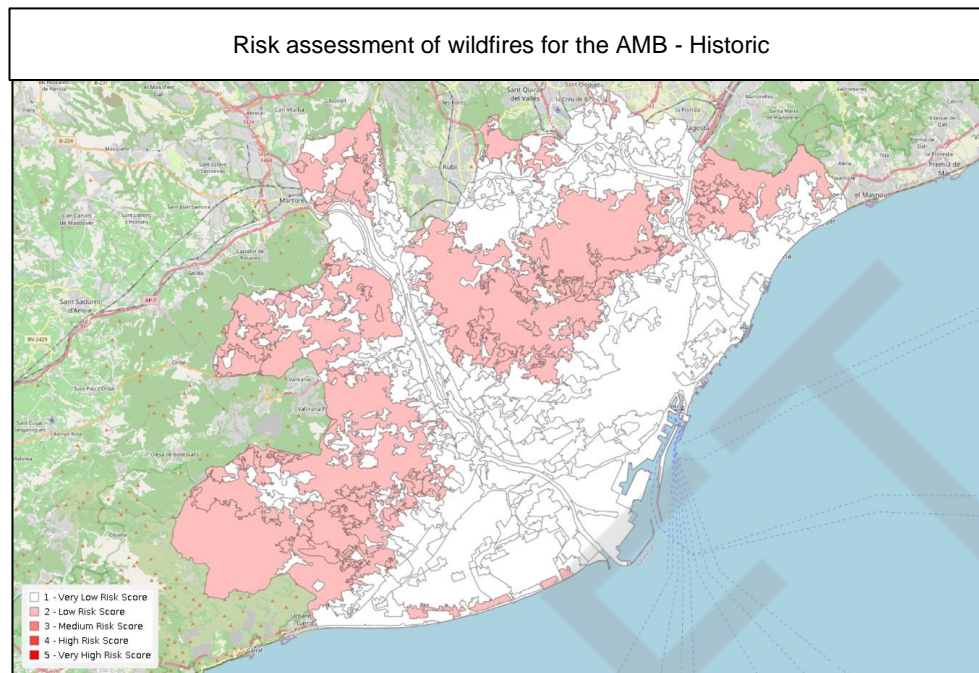
Results of the impact assessment for wildfires on the AMB done with the DSS show no change through the scenarios analysed. This is due to the little change in the hazard data, as explained before and shown in the figure below. The increase of FWI>38 days is too small to surpass the threshold of +40 days needed for the DSS tool to establish a higher hazard level.



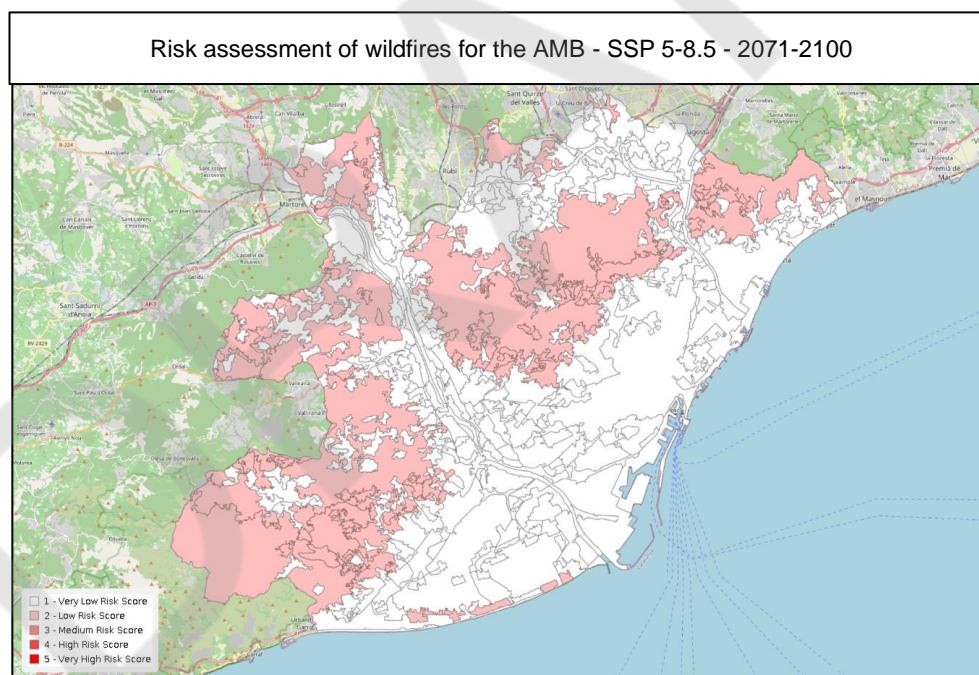
**Figure 47.** Hazard map comparison for the AMB.

As shown in Figure 47, in the historic period, days with FWI>38 during a standard year are mostly below 7, reaching up to 16 in very small and vulnerable areas. For the furthest future scenario, most of the area is within the 0-15 days threshold, and the most vulnerable areas increase up to 32 days of FWI>38.

Figures 48 and 49 show that there is no difference between the historic and future projection scenarios.



**Figure 48.** Risk map of wildfires for the AMB, Historic period.

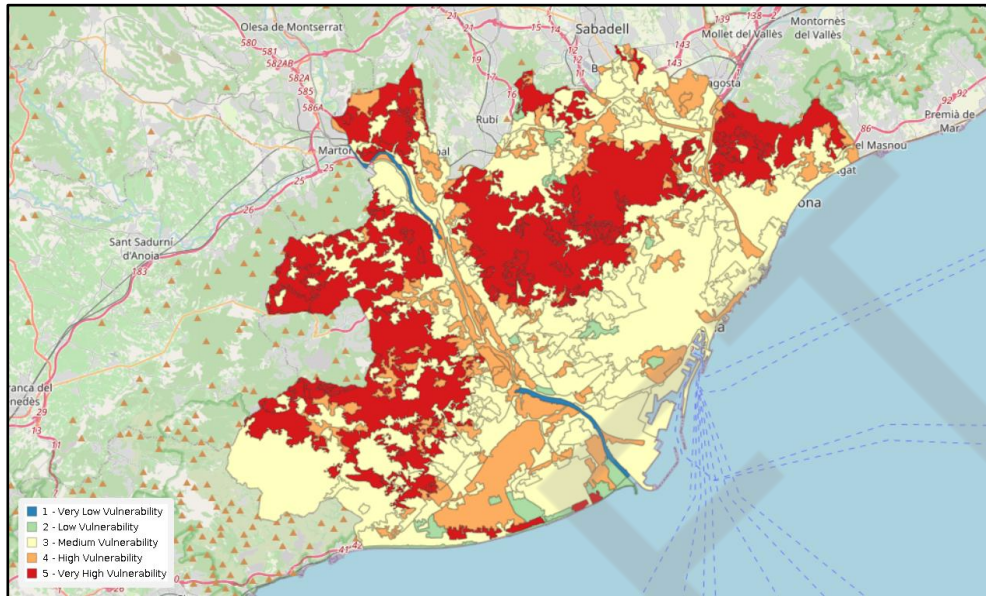


**Figure 49.** Risk map of wildfires for the AMB, SSP5-8.5, 2071-2100 period.

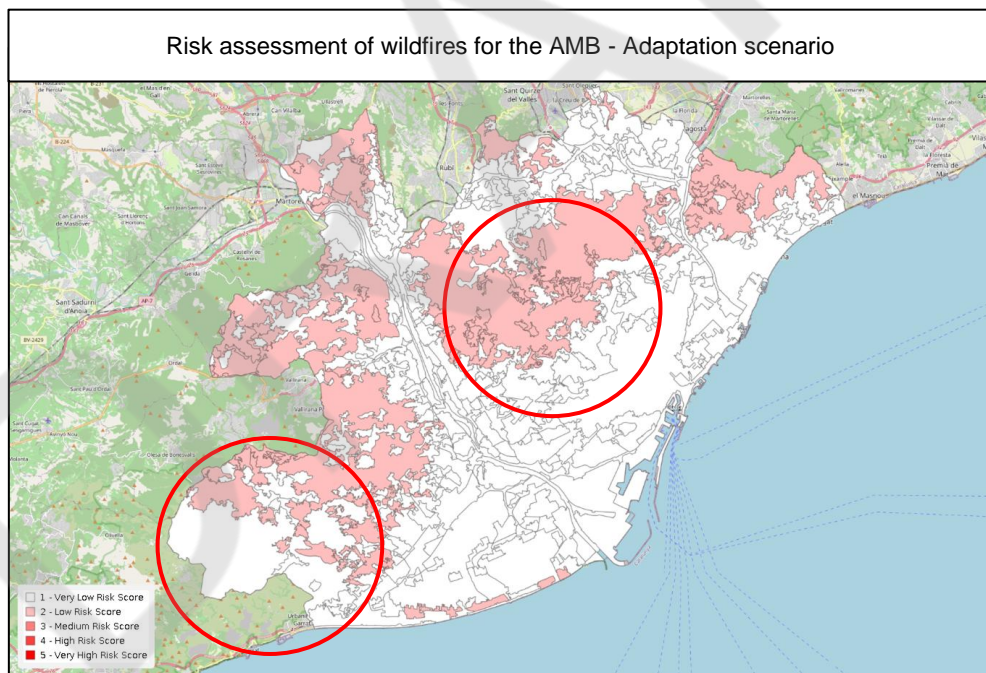
### Adaptation scenario

In order to reduce the vulnerability of specific areas, especially those near the city limits and bordering forest areas, measures from the ICARIA Adaptation Portfolio were applied to the adaptation scenario. The adaptation measure titled “Keep sufficient space in the soil and subsoil to allow for the necessary climate services” improves the infiltration of water into the soil and its quality, thus

reducing its vulnerability to wildfires. Figure 50 shows the new adaptation map created using the DSS, while Figure 51 shows the related risk map.



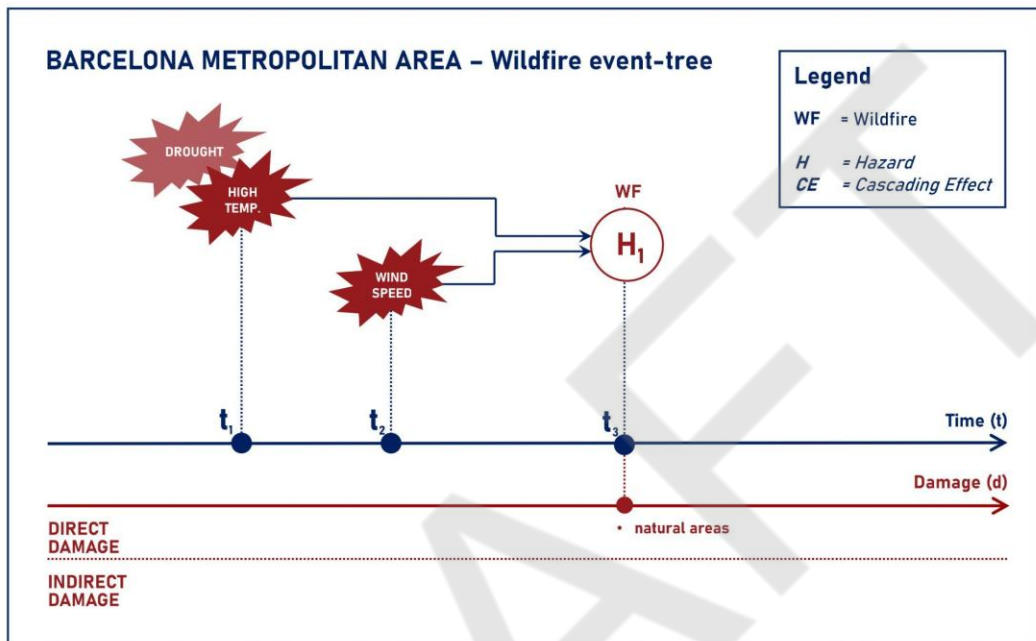
**Figure 50.** Vulnerability map of the AMB for the adaptation scenario created with the DSS.



**Figure 51.** Risk map of wildfires for the AMB, adaptation scenario.

#### 4.1.6. Wildfire impact and adaptation: expert-based insights

The wildfire Mini-trial for the AMB CS is structured around a single-hazard event-tree scenario representing the temporal sequence of processes and impacts associated with wildfire events (Figure 52).



**Figure 52.** Wildfire event-tree scenario for AMB Mini-trial (replication phase).

The triggering conditions include dry weather and high temperatures ( $t_1$ ), combined with wind speed ( $t_2$ ), creating a favourable setting for fire ignition. Wildfires then emerge as the main hazard ( $t_3$ ), mainly causing direct short-term damage to natural areas ( $t_3$ ). The sequence of events (triggering conditions and main hazard) reflects a rapid-onset impact pathway in which impacts materialise shortly after fire ignition. Impacts include loss of vegetated/semi-vegetated areas, with limited cascading effects beyond the areas directly affected by the fire.

Within this targeted event-tree scenario, the **ICARIA modelling framework is considered applicable primarily at the local scale and over temporal horizons ranging from hours to days**. The modelling process behind hazard and impact assessment is based on the Fire Weather Index (FWI), derived from basic climate variables. Exposure information for assets at risk can be obtained from publicly available data repositories. In this context, the **performance of the ICARIA modelling framework is expected to be moderately dependent on the quality and spatial resolution of the input datasets**. Taken together, these aspects support the internal coherence and methodological robustness of the wildfire modelling workflow, thereby informing **RQ-Sci1** regarding the scientific plausibility and reliability of the modelling results.

From a data requirements and technical constraints perspective, the **effort required to prepare input data for replication is assessed as low**, reflecting limited harmonisation and preprocessing requirements. In line with this assessment, no specific contextual factors or structural limitations

were identified as significantly constraining replication in other contexts. The main data-related barriers are associated with fragmented or heterogeneous data sources. Overall, these findings suggest a relatively low structural sensitivity of the modelling configuration to contextual data conditions and calibration requirements, contributing to **RQ-Sci3** by indicating limited immediate needs for methodological refinement, while also positively informing the technical feasibility dimension of **RQ-Sci2**.

Considering the expected outputs, the replication of the wildfire Mini-trial is anticipated to generate fire risk maps providing spatially explicit risk scores at square-kilometre (km<sup>2</sup>) spatial resolution. These outputs are directly relevant for assessing wildfire exposure and supporting targeted wildfire risk/impact management measures, particularly in the context of emergency preparedness and spatial planning. The adaptation measure considered within this scenario consists of maintaining sufficient space in the soil and subsoil to enable the provision of essential climate services. According to the expert, the **ICARIA DSS fully supports the modelling workflow required for the wildfire event-tree scenario** during the replication phase across all modelling components ('elementary bricks'). This full workflow support reflects a high degree of operational maturity and system integration in its current configuration, directly informing **RQ-Sci2** with regard to the practical ease of application, and contributing to **RQ-Sci4** by demonstrating a functional level of integration comparable to conventional wildfire risk/impact assessment approaches.

With respect to replication effort and resource implications, the main cost driver is personnel time required for framework configuration and modelling activities. **The overall cost required to replicate the ICARIA modelling framework is estimated at less than €10,000, with a typical implementation timeframe of under 1 month.** The most time-consuming step is expected to be data collection and preparation. While data collection and preparation are expected to be the most time-consuming steps, no specific obstacles were identified as potentially delaying replication or increasing costs, as the modelling workflow is considered relatively simple and easily replicable. These findings provide structured evidence addressing **RQ-Sci2**, particularly in relation to the economic, temporal, and organisational feasibility of applying the wildfire modelling workflow in new contexts.

#### 4.1.7. Stakeholder-based insights on impact and adaptation across hazards in the AMB case study

This section summarises the responses to the ICARIA questionnaire from the AMB CoP-engaged stakeholders across Trials (ADVANCED VERSION) and Mini-trials (BASE VERSION), integrating interpretative insights with references to the project's research questions (i.e., RQ-Sci1-4 on scientific validity, RQ-Ex1-3 on usability, RQ-Acc1-4 on acceptance, RQ-Soc1-2 on socio-economic relevance, and RQ-Sus1-2 on sustainability), as outlined in the methodological Section 3.1.4.2. Responses from three key stakeholders – technical staff from municipal/regional utility companies (water/energy/transport) and a national-level NGO analyst – reveal a pragmatic endorsement of the ICARIA modelling framework, emphasising demonstration feedback and replication interest, balanced by calls for contextual adaptation, validation, and operational integration in order to enable replication beyond CSs.

### Respondent profile and Organisational needs and priorities

The respondent profiles represented in the responses suggest that, in particular within the AMB CoP, ICARIA engages stakeholders who are structurally close to critical decision-making chains in climate risk management, but who differ markedly in terms of their institutional mandate and technical capacity. Utility companies at municipal and regional levels operate under strict regulatory and service-continuity constraints. Their technical staff tend to frame climate risk/impact primarily in terms of infrastructure safety, the continuity of energy and water supply, and regulatory compliance. This naturally leads to a focus on hazards and cascading network disruptions that could compromise essential services. By contrast, the NGO respondent, which operates at the national scale with advanced expertise, approaches climate risk/impact through a more analytical, cross-sectoral lens, paying attention to methodological robustness, hazard combinations, and transferability of models. The coexistence of 'basic' and 'advanced' experience levels among its respondents indicates that the ICARIA modelling framework needs to accommodate both sophisticated analytical users and practitioners whose primary expertise lies in operations rather than modelling. The fact that climate risk/impact assessments are often conducted only when required by regulation, as revealed by the questionnaire, highlights a reactive institutional culture and suggests that the added value of ICARIA could be to support a gradual transition towards more systematic, anticipatory risk management.

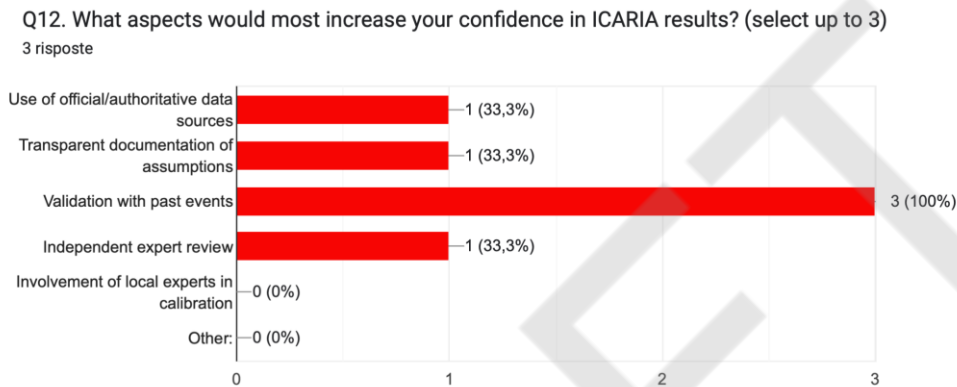
### Knowledge and use of existing risk/impact assessment tools

The **limited use of digital tools among utility respondents contrasts with the reliance of the NGO on existing platforms** such as CLIMADA (<https://wcr.ethz.ch/research/climada.html>), AdapteCCa (<https://adaptecca.es/en>) or Copernicus (<https://climate.copernicus.eu/>). This reveals a **structural divide between research-oriented and operational users**. Operational actors may rely more on ad hoc studies, consultancy reports, or in-house GIS than on integrated, multi-hazard modelling environments. This has two implications. Firstly, **existing tools are not perceived as fully embedded in day-to-day decision-making processes**, resulting in new frameworks like ICARIA finding it difficult to replace or complement them unless they can demonstrably reduce complexity or workload. Secondly, qualitative descriptions of **limitations such as insufficient spatial resolution, the absence of multi-hazard and cascading effect modelling, and weak integration of impacts**, align closely with ICARIA's stated scientific ambitions. In this sense, stakeholders implicitly validate the project's diagnosis of the problem: **current tools often fail to capture the systemic, interconnected nature of climate risks/impact**. However, the fact that these limitations are articulated more clearly by the NGO than by utilities suggests that advanced features (e.g., compound events, cascading failures) will be particularly appreciated by analytically oriented users, whereas utilities may prioritise reliability, clarity, and sector-specific outputs over methodological sophistication per se.

### Plausibility and reliability of ICARIA data and modelling results

The consistently high credibility ratings and the perception that the **input data are "mostly representative"** suggest that, at least for the cases examined, ICARIA has successfully navigated one of the core barriers identified in the questionnaire design: the need to demonstrate **scientific plausibility and contextual relevance**. The emphasis placed by stakeholders on validation against

past events, the use of authoritative data sources, and transparent documentation of assumptions is not merely a technical requirement; it reflects a broader governance logic in which climate risk/impact assessments may be contested by internal departments, regulators, or the public. In this sense, credibility is both epistemic and political. Furthermore, the expressed desire for independent expert review further underlines that **AMB stakeholders view ICARIA outputs as potentially decision-shaping and requiring a high degree of external legitimacy** (Figure 53).



**Figure 53.** Distribution of AMB stakeholder responses to Question 12 (Q12) of the questionnaire.

#### Perceived Benefits and Use Cases

Stakeholders' descriptions of the usefulness of ICARIA move beyond generic appreciation and point to concrete, practical use cases. For utilities, the **possibility of visualising flood impacts on transport or energy networks is not just a visualisation** feature but a way of translating complex hazard information into operationally meaningful scenarios. This sector-specific mapping supports both emergency planning and long-term investment decisions. For the NGO, the **added value lies in the capacity to support climate adaptation planning and design**, where consistent risk metrics across territories facilitate comparative analysis and prioritisation. The fact that **ICARIA is rated as "somewhat better" or "significantly better" than existing tools** suggests that stakeholders view it as an opportunity to develop a framework that consolidates heterogeneous information into more practical outputs that can be embedded in recurrent planning and regulatory processes, thereby shifting from a 'project tool' to a 'reference framework'.

#### Cost Acceptability and Replication Feasibility

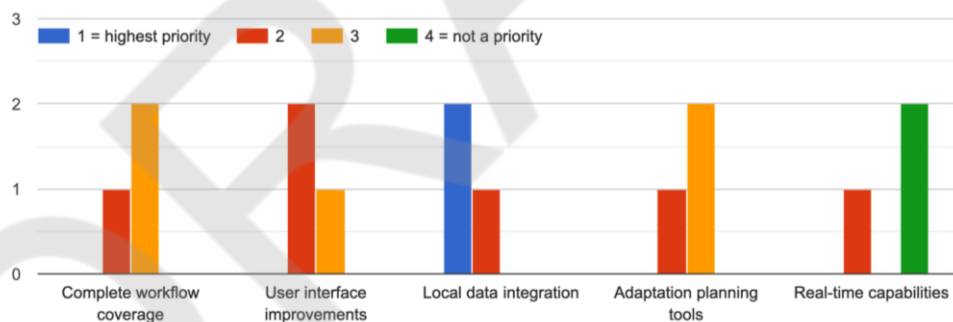
Stakeholders' judgments on cost and effort shift the focus of the analysis from scientific desirability to organisational realism. In general, without differentiating the responses regarding the BASE VERSION from the ADVANCE VERSION, the stakeholders view the **estimated investment required for replication of the framework as "acceptable if benefits are clear"**. The ranking of cost components indicates that stakeholders are relatively **more tolerant of expenses associated with data acquisition and processing**, which they may perceive as inevitable. However, they are more **reluctant to absorb the cost of ongoing maintenance and staff time**, as these directly compete with other institutional priorities. The classification of technical demands as *"moderate, with some external support needed"* suggests a specific adoption model: ICARIA is not seen as 'plug-and-play',

but neither as prohibitive; it will require partnerships, external expertise, or centralised support structures. **Timelines (even longer than six months for the ADVANCED VERSION) are acceptable** under conditions (e.g., intermediate outputs, guarantees of quality), indicating a **willingness to engage in iterative, multi-stage implementation** rather than expecting an immediate payoff.

Interest in the DSS component

**The evaluation of the DSS highlights the importance of user experience as a mediating factor between technical capabilities and actual adoption.** Stakeholders repeatedly emphasise features that reduce cognitive and operational burden: a clear and responsive interface, automated reporting, real-time or near-real-time updating where relevant, and seamless integration with existing systems and workflows. For utilities, the DSS is attractive insofar as it can provide single-hazard, high-relevance workflows (e.g., pluvial flood alerts), while leaving room to expand toward multi-hazard complexity once trust has been established. For the NGO, the value lies more in multi-user collaboration, scenario building, and the ability to support multi-level planning processes. The ranking of development priorities – often favouring **complete workflow coverage, user interface enhancements, and local data integration over more advanced real-time capabilities** – suggests that stakeholders currently give more weight to reliability, clarity, and integration than to cutting-edge functionality (Figure 54). This aligns with the questionnaire’s focus on ease of use, ease of understanding outputs, and perceived usefulness as preconditions for routine operational integration.

Q41. Rank your top 3 priorities for DSS development/enhancement:

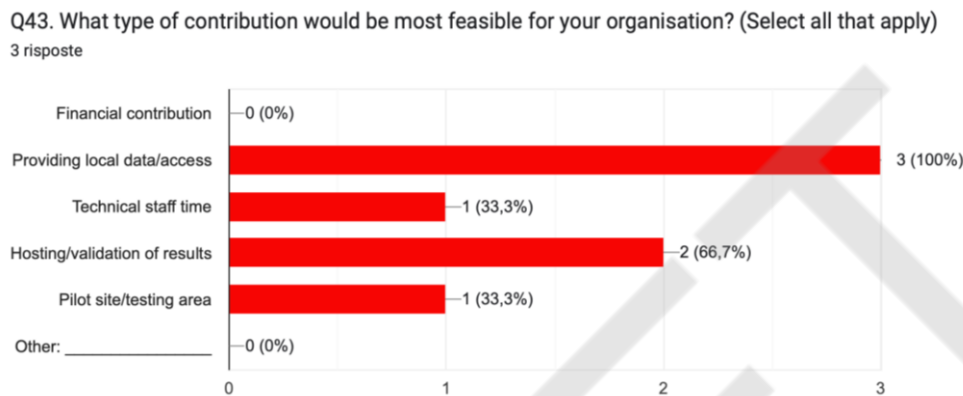


**Figure 54.** Distribution of AMB stakeholder responses to Question 41 (Q41) of the questionnaire.

Contributions, Socio-economic Impacts, and Ethics

The stakeholders’ willingness to contribute primarily through in-kind resources (e.g., data, staff time, hosting) illustrates a pragmatic commitment: **stakeholders are prepared to invest their own capacities where they see strategic value, but they are more cautious regarding direct financial contributions.** This pattern supports replication strategies that leverage co-production and data-sharing agreements rather than expecting full-cost recovery from end users. Utility representatives express unequivocal commitment to contributing through partnerships and in-kind resources, encompassing local data access, technical staff time, software integration, hosting capabilities, and result validation. The municipal utility delineates a comprehensive portfolio, including dedicated

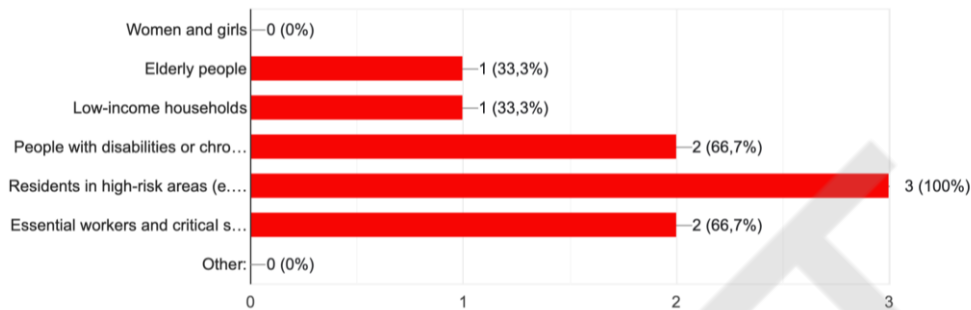
personnel for calibration (Figure 55). This configuration of commitments constitutes a scalable co-production architecture that seems to minimise financial barriers whilst maximising knowledge exchange and local ownership, thereby constituting a robust foundation for the BASE VERSION's sustainability and transferability beyond the project remit (RQ-Sus2).



**Figure 55.** Distribution of AMB stakeholder responses to Question 43 (Q43) of the questionnaire.

In terms of socio-economic impacts, stakeholders anticipate that ICARIA can support more efficient targeting of resilient infrastructure investments, reduce economic losses from climate events, and improve protection for vulnerable groups. However, the **articulation of gender and broader social equity issues remains relatively generic**, often framed in terms of ‘vulnerable groups’ without detailed differentiation. This may suggest that the equity potential identified in the questionnaire design is only partially realised at the stakeholder level and may require more explicit guidance or indicators within the tools themselves. Equity potential seems, in fact, feasible across responses, yet it manifests heterogeneous articulations that show divergent vulnerability conceptualisations. The regional utility furnishes the most comprehensive taxonomy, encompassing elderly populations, low-income households, persons with disabilities or chronic illnesses, residents of high-risk areas (flood-prone zones and urban heat islands), and essential workers in critical services. This granularity enables spatially- and socially-differentiated risk/impact prioritisation, aligning single-hazard outputs with targeted adaptation measures. The NGO references persons with disabilities or chronic illnesses and residents in high-risk areas, prioritising physical vulnerability over socio-economic mediation – a reflection of analytical traditions favouring quantifiable exposure metrics. Despite questionnaire prompting, **no respondent disaggregates vulnerability by gender**, showing a conspicuous absence of gender considerations that constitutes a structural omission warranting future scrutiny (Figure 56).

Q48. In your view, which groups could benefit most from ICARIA-informed decisions? (select all that apply)  
3 risposte



**Figure 56.** Distribution of AMB stakeholder responses to Question 48 (Q48) of the questionnaire.

Stakeholder **expectations regarding the socio-economic impacts** of ICARIA show a spectrum of optimism, revealing both the framework's immediate practical promise and the conceptual scaffolding required for transformative social impact (RQ-Soc1-2). Utility respondents attribute moderate socio-economic impacts to the use of the framework, with the municipal representative emphasising improved targeting of resilient infrastructure investments and enhanced protection of vulnerable groups and neighbourhoods. The regional utility escalates this to high impacts, incorporating reduced economic losses from climate-related events alongside improved protection of vulnerable groups, indicative of a systems-level perspective that aggregates asset-specific gains into broader economic resilience narratives suited to regional governance scales.

#### 4.1.7.1. Responses specific to the ICARIA BASE VERSION (Mini-trials)

As outlined in Section 3.1.4.2, the ICARIA stakeholder questionnaire comprises two distinct sets of questions for the BASE VERSION (Mini-trials) and ADVANCED VERSION (Trials), reflecting their different methodological scope and replication requirements. The BASE one focuses on a streamlined, single-hazard configuration suitable for rapid deployment in data-sparse contexts, addressing usability, cost feasibility at lower technical thresholds, and operational applicability. In contrast, the ADVANCED one targets compound-hazard scenarios with cascading effects, emphasising more complex modelling requirements, extended timelines (e.g., >6 months), and enhanced analytical features (e.g., uncertainty representation). For the purpose of this deliverable, the responses presented here refer exclusively to the BASE VERSION and are structured around Mini-trials.

The AMB Mini-trials encompassed key climate hazards, including droughts, heatwaves, and wildfires, ensuring comprehensive hazard coverage in the assessment toolkit. Respondents were presented with a unified set of questions, addressing estimated replication costs, timelines, technical demands, data constraints, and improvement needs across all hazards (Table 14). This approach enabled stakeholders to evaluate the transferability and scalability of the ICARIA framework within other contexts without hazard-specific prompting, thus capturing an integrated perspective of replicability.

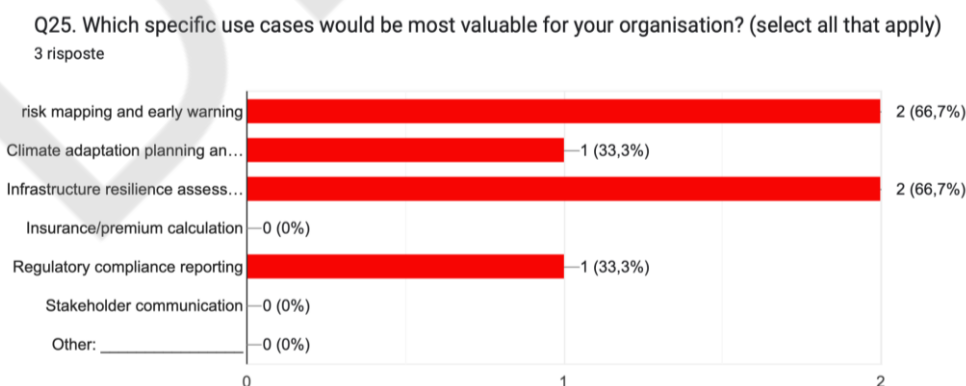
**Table 14.** Key climate hazards included in AMB Mini-trial and the effort required (costs and time) for replication in other contexts.

Effort required	Hazard		
	Droughts	Heatwaves	Wildfires
Expected cost for replication (€)	20,000–50,000	10,000–20,000	<10,000
Expected time for replication	3-6 months	1-3 months	<1 month

Overall, responses show a high degree of consistency among the three stakeholders, including technical staff from municipal and regional utility companies and a national-level NGO analyst. This convergence underscores the positioning of the BASE VERSION as a streamlined, single-hazard risk/impact assessment tool suitable for resource-constrained environments, offering accessible entry points for practitioner-led applications, while also pointing to limitations in methodological depth and context-specific calibration.

Perceived Utility and Application Domains

The evaluation of the **BASE VERSION can be considered useful for all the respondents (“quite useful” from the utilities’ representatives and “slightly useful” for the NGO)**. Utility representatives emphasise its immediate usefulness to risk/impact mapping and early warning systems, coupled with infrastructure resilience assessment, conceptualising the tool as an operational enabler for critical network protection (e.g., metro and energy systems vulnerable to pluvial flooding). The regional utility extends to regulatory compliance reporting, reflecting the periodicity of its annual assessment cycles and highlighting the BASE VERSION's alignment with statutory obligations. By contrast, the NGO accords priority to climate adaptation planning and design, evidencing a more strategic orientation that transcends immediate operational imperatives. Collectively, these application domains affirm the **BASE VERSION's appeal within practitioner contexts, delivering concrete benefits for urban planning and risk management** without the computational or expertise demands of advanced compound modelling (RQ-Acc1) (Figure 57).



**Figure 57.** Distribution of AMB stakeholder responses to Question 25 (Q25) of the questionnaire.

### Comparative Performance and Strategic Value

Both utility representatives evaluate the **BASE VERSION "somewhat better" than existing tools, attributing this superiority to detailed, sector-specific information** – exemplified by the municipal respondent's reference to "*detailed information about flooding in the metro network*" – **and enhanced impact visualisation capabilities**. The NGO rates it "*significantly better*" with emphasis on adaptation to specific environmental contexts. Strategic value propositions exhibit **convergence around operational relevance**: the regional utility values its official organisation, the municipal prioritises network-specific insights, and the NGO underscores contextual tailoring. These attributes position the BASE VERSION as a compelling alternative to ad hoc methodologies or the limited multi-hazard capacities of existing platforms such as CLIMADA and Adapteca, particularly for baseline single-hazard requirements (RQ-Sci4).

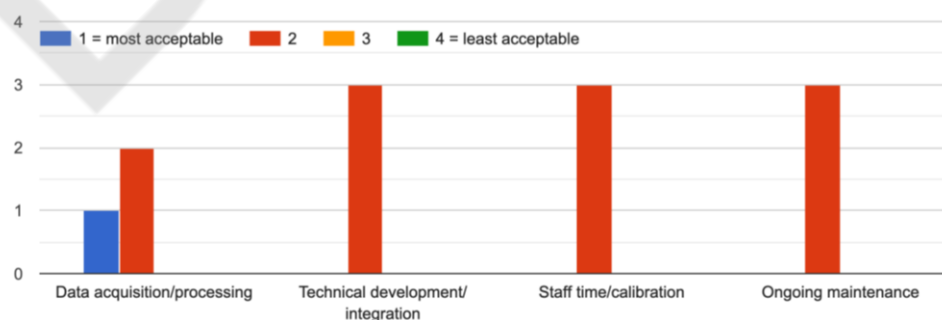
### Data Gap-Filling Methodologies

**Satisfaction with the BASE VERSION's data gap-filling approaches – encompassing proxies, assumptions, and model-based interpolations – remains notably neutral.** Utilities profess unfamiliarity ("*I am not familiar*"), attributing this position to "*modelling not being our main field of expertise*", whilst the NGO registers "*neither satisfied nor dissatisfied*" (RQ-Sci1).

### Cost Acceptability and Replication Feasibility

The proposed investment range (i.e., **€20,000–50,000 for droughts, €10,000–20,000 for heatwaves, and €<10,000 for wildfires**) for replicating the ICARIA BASE VERSION in new contexts elicits unanimous conditional acceptance across all respondents, qualified by the response "**acceptable if benefits are clear**". This consensus mirrors stakeholders' sentiments towards the ADVANCED VERSION (here not reported), suggesting the cross-configurational affordability of the ICARIA framework independently from its methodological complexity. Cost component rankings seem to suggest levels of acceptability that consistently privilege data acquisition and processing (ranked 1-2 across respondents) over technical development, staff time, calibration, and ongoing maintenance (predominantly ranked 2) (Figure 58).

Q31. Rank the following cost components from most to least acceptable (1 = most acceptable; 4 = least acceptable):



**Figure 58.** Distribution of AMB stakeholder responses to Question 31 (Q31) of the questionnaire.

This preferential ordering underscores stakeholder tolerance for upfront capitalisation in data infrastructure – proprietary network inventories, exposure databases, quality validation – anticipated to yield discernible operational returns through enhanced risk mapping and decision support. **Technical replication demands register as "moderate, with some external support needed"** across respondents. **Timeline willingness diverges pointedly** (i.e., 3-6 months required for droughts, 1-3 months for heatwaves, and <1 month for wildfires): utilities affirm acceptance "Yes" (conditional on quality assurances or intermediate deliverables), whereas the NGO demurs "*No, results needed sooner*", citing hazard misalignment (floods, droughts, compounds extraneous to core interests). (RQ-Sus2).

## 4.2. Salzburg Region CS

This section presents the Mini-trials developed for the SLZ CS within Task 4.3. In line with the overarching objectives of the Mini-trials, the SLZ activities address heatwave and wildfire risk/impact modelling under climate change scenarios based on the SSPs framework (SSP1-2.6 and SSP5-8.5), with the dual aim of assessing transferability and replicability of the ICARIA methods and tools and evaluating the socio-economic implications arising from their implementation. The two hazard scenarios follow distinct design configurations: the **wildfire Mini-trial builds upon the Trial architecture developed and implemented within the SAR CS**, adapted and simplified to serve transferability and replicability purposes; the **heatwave Mini-trials, by contrast, is implemented as stand-alone simplified assessments**, not directly derived from a prior Trial framework, and entail an explicit knowledge and approach transfer across CSs.

For each hazard type, Mini-trials describe targeted event-tree scenarios, spatial and temporal scales of application, key input data requirements and modelling assumptions, as well as the main outputs relevant for decision-making and adaptation planning. In addition to presenting the modelling results, the following subsections integrate evidence derived from both expert and stakeholder questionnaires administered during the Mini-trial phase. This combined presentation of modelling outputs, expert-based technical assessment, and stakeholder-based evaluations provides a structured basis for addressing Task 4.3 purposes.

### 4.2.1. Heatwave impact and adaptation: modelling implementation

The impact of heatwaves on human health was assessed by combining high-resolution climate projections with demographic data and vulnerability functions. In particular, temperature outputs derived from the Weather Research and Forecasting (WRF) regional climate model were used to characterise the heatwave hazard, while vulnerability curves from Ledebur et al. (2025) were applied to estimate heat-related excess mortality within the Salzburg region.

#### Risk assessment methodology

The risk of heat-related excess mortality was estimated by integrating three core components of the ICARIA modelling framework:

- Hazard, represented by temperature time series derived from climate model simulations;
- Exposure, represented by the spatial distribution and demographic structure of the population;
- Vulnerability, represented by temperature–mortality relationships derived from empirical studies.

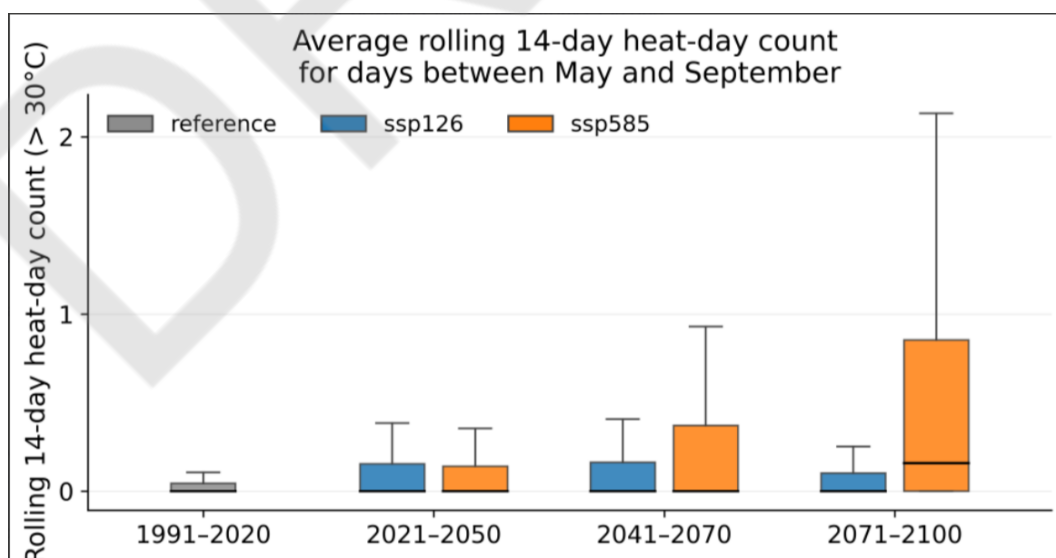
The analysis was conducted over the full simulation period (2020–2100). However, it is important to acknowledge that the reliability of the vulnerability functions decreases towards the end of the century, as projected temperature conditions may exceed the range observed in the historical data used for their calibration. This introduces additional uncertainty in long-term mortality estimates.

#### Hazard assessment

**Heatwave hazard** was derived from **WRF model outputs under the SSP5-8.5 climate scenario** and defined based on the occurrence of high-temperature events. Specifically, heatwave conditions were identified as the **number of days with Tmax exceeding 30°C within a 14-day moving window**.

Unlike conventional climatological analyses, no aggregation into 30-year periods was performed. This choice was made to preserve short-term variability and capture extreme heatwave events, which are more relevant for assessing acute health impacts during particularly hot summers.

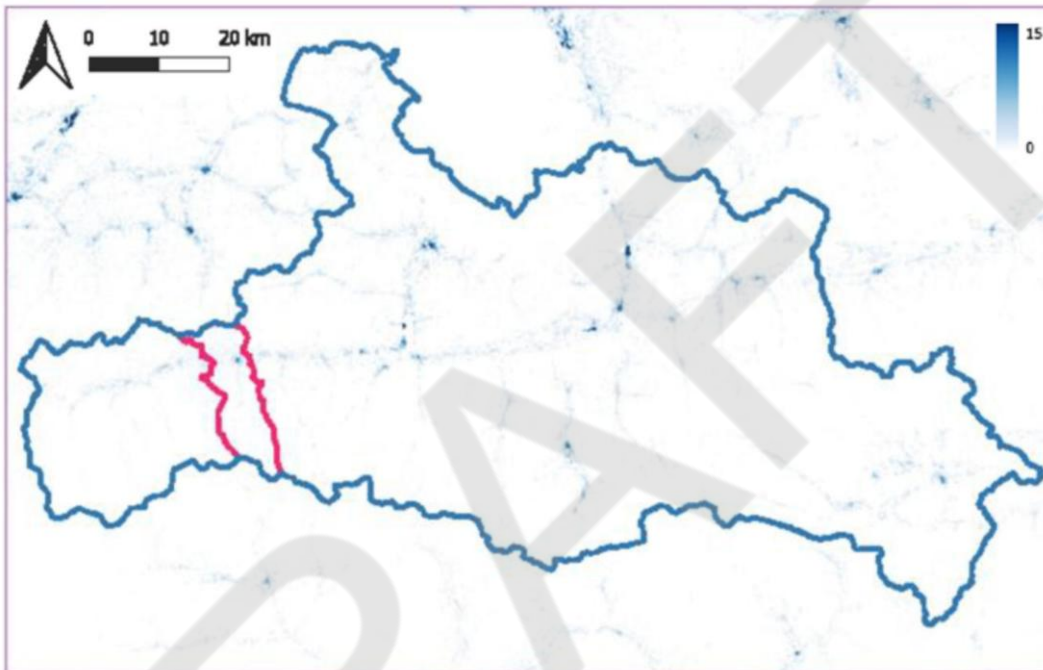
To further characterise the temporal structure of heatwave events, the **distribution of hot days (Tmax >30°C) within the 14-day rolling window** was analysed (Figure 59). Results indicate that sequences of consecutive hot days remain relatively limited, particularly under lower-emission scenarios (e.g., SSP1-2.6), while a wider variability and higher upper extremes emerge under the SSP5-8.5 scenario, especially towards the end of the century. This supports the use of a moving-window approach to capture short-term heat accumulation effects relevant for health impact assessments.



**Figure 59.** Distribution of hot days (Tmax >30 °C) within a 14-day rolling window (May–September), aggregated over the study domain for historical and future climate scenarios.

## Exposure assessment

**Population exposure** was characterised using the **WorldPop dataset** (<https://hub.worldpop.org/geodata/summary?id=80207>) **at 100 m<sup>2</sup> spatial resolution**, which provides detailed information on population distribution and age structure (Figure 60). For the analysis, the population was aggregated into three age groups: 0–45 years, 45–65 years, and >65 years. This classification allows capturing age-dependent vulnerability to heat stress, which is a key determinant of heat-related excess mortality.

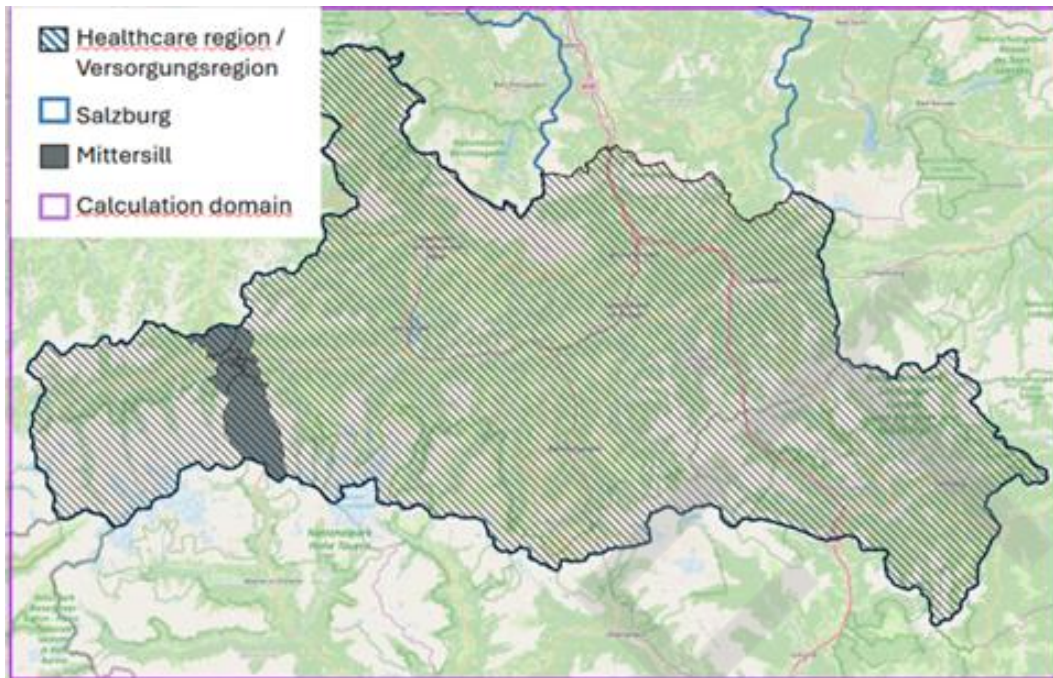


**Figure 60.** Exposure, expressed as the number of people per 100 m<sup>2</sup>.

## Vulnerability assessment

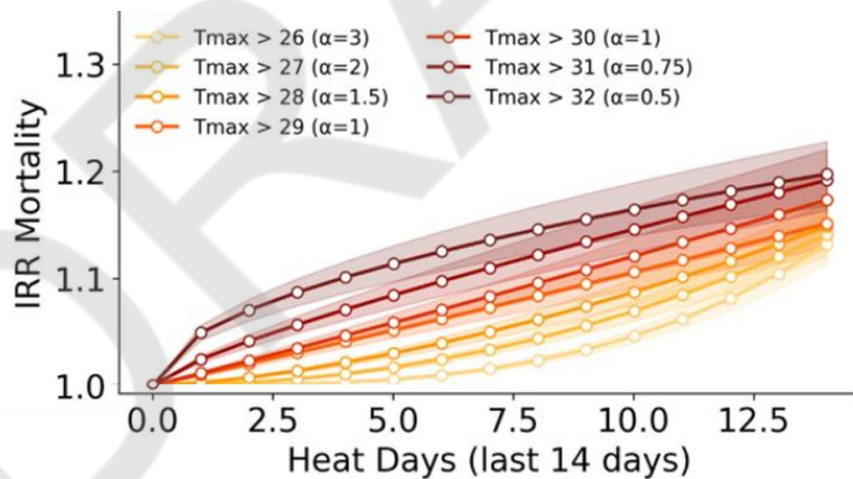
The **vulnerability of the population to heat stress** was assessed using **empirical vulnerability functions derived within the HeatProtect project** (<https://projekte.ffg.at/projekt/4847510>; Ledebur et al., 2025). These functions describe the relationship between heat exposure and the relative increase in mortality risk, differentiated by age group. More specifically, the vulnerability curves relate the number of hot days – defined as days with Tmax exceeding 30°C – within a 14-day time window to an increase in mortality risk. This approach allows capturing the cumulative effects of sustained heat exposure on human health.

For the SLZ CS, the vulnerability functions were **calibrated based on healthcare data from the regional health system** (Figure 61), covering the period 2014–2019. The analysis reflects region-specific epidemiological conditions and demographic characteristics.



**Figure 61.** Healthcare region adopted for computing the vulnerability functions. The dark grey area represents Mittersill, the focus area of the Mini-trial.

Results show a marked non-linear increase in vulnerability when  $T_{max}$  exceeds  $30^{\circ}\text{C}$ , indicating a threshold beyond which heat-related health impacts intensify significantly (Figure 62).



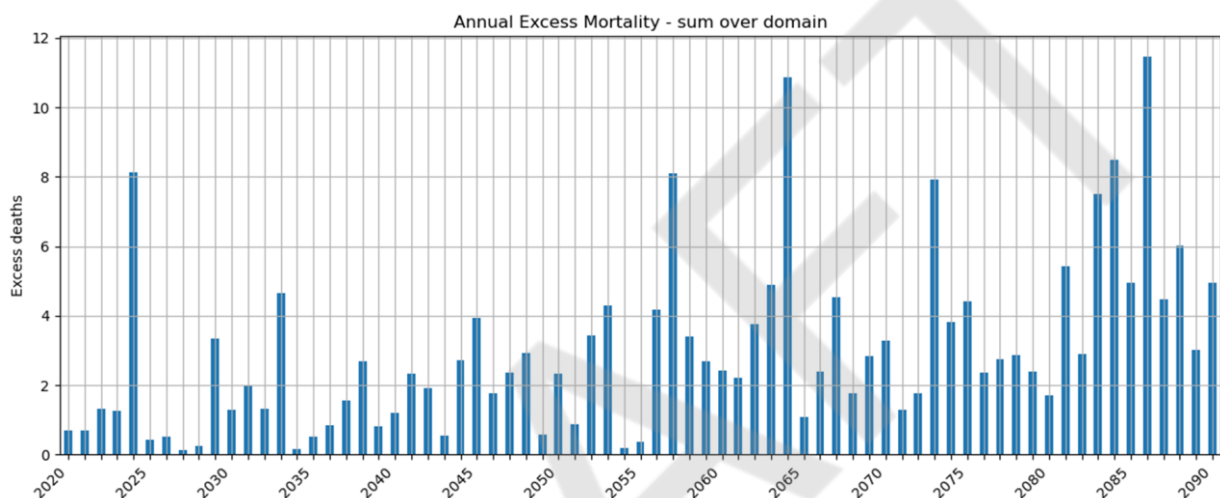
**Figure 62.** Relationship between heat days ( $T_{max} > 30^{\circ}\text{C}$ ) and IRR mortality, with a clear non-linear increase.

#### Heatwave Risk Assessment

The estimation of **heat-related excess mortality** should be interpreted as a **preliminary assessment**, subject to important limitations. In particular, the **vulnerability functions are derived from historical health data** (2014–2019; Ledebur et al., 2025), and their validity under future climate conditions – especially under the SSP5-8.5 scenario – remains uncertain. Projected temperatures

may exceed the range of observed conditions used for calibration, potentially leading to under- or over-estimation of impacts.

For the analysed healthcare region, the estimated excess mortality associated with heat events remains relatively low for most years, typically below two additional deaths across the entire study area. However, in years characterised by more intense and persistent heat conditions – particularly in the second half of the century under more severe climate scenarios – excess mortality is projected to increase substantially, reaching **up to approximately 10–11 additional deaths per year at the regional scale** (Figure 63), which is about five times higher than the average.

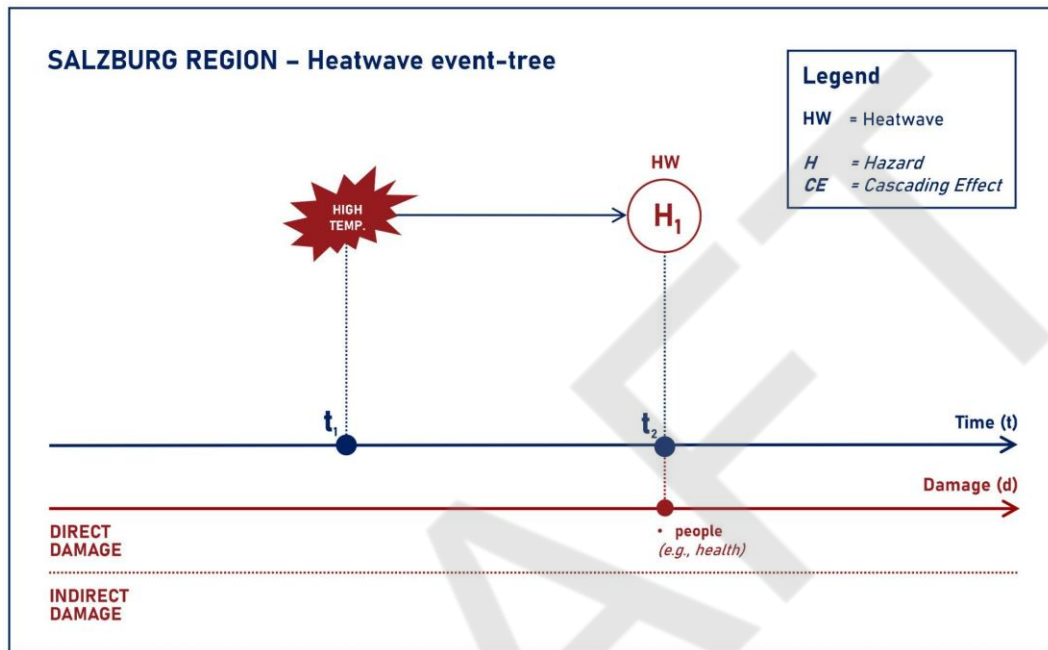


**Figure 63.** Regional excess deaths due to heat ( $T_{max} > 30\text{ °C}$ ) under the SSP5-8.5 scenario.

No adaptation measures were considered in this scenario; therefore, the results reflect a baseline assessment of potential impacts under a no-adaptation assumption.

#### 4.2.2. Heatwave impact and adaptation: expert-based insights

The heatwave Mini-trial for SLZ CS is structured around a single-hazard event-tree scenario representing the temporal sequence of processes and impacts associated with extreme heat (Figure 64).



**Figure 64.** Heatwave event-tree scenario for SLZ Mini-trial (replication phase).

The triggering event corresponds to a sustained increase in air temperature ( $t_1$ ), operationally defined as maximum temperatures exceeding specific thresholds (e.g., 30 °C), which gradually evolves into a heatwave event ( $t_2$ ), represented by the number of days >30 °C within a 14-day time window. Once heatwave conditions are established, high temperatures intensify thermal stress within the urban/extra-urban environment, causing direct short-term damage to people ( $t_2$ ). The sequence of events (triggering event and main hazard) reflects a rapid-onset impact pathway, whereby impacts materialise shortly after the triggering conditions. Impacts include adverse effects on human health, particularly among vulnerable population groups (e.g., people aged over 65), with limited cascading effects beyond immediate heat-related stress mechanisms.

Within this targeted event-tree scenario, the **ICARIA modelling framework is considered applicable primarily at the local scale and over temporal horizons limited to days**. The modelling process underlying heatwave hazard and impact assessment relies on a configuration requiring detailed and accurate regional climate information as well as usable vulnerability curves. In this context, the **performance of the ICARIA modelling framework is expected to be largely dependent on the quality and resolution of the climate datasets, as well as on the reliability and representativeness of vulnerability curves**, which in turn are influenced by the level of characterisation of the elements at risk. Taken together, all these aspects support the internal coherence and methodological robustness of the heatwave modelling workflow, thereby informing **RQ-Sci1** regarding the scientific plausibility and reliability of the modelling results.

From a data requirements and technical constraints perspective, the **effort needed to prepare input data so that they are ICARIA-ready is assessed as moderate**, as it relies on accurate climate information and on well-characterised exposure data, which underpin vulnerability assessment and the derivation of appropriate vulnerability curves. The availability and quality of hazard and exposure/vulnerability parameters are considered key factors influencing successful replication in other contexts. The main data-related barriers are associated with insufficient documentation or metadata (e.g., limited observed damage), as well as missing mandatory variables, which may hinder harmonisation and integration across contexts. These elements highlight the sensitivity of the modelling configuration to contextual data conditions and calibration requirements, contributing to **RQ-Sci3** by identifying areas where further methodological refinement may be needed, while also informing the technical feasibility dimension of **RQ-Sci2**.

Considering the expected outputs, the replication of the heatwave Mini-trial is anticipated to generate high-resolution surface heat maps representing temperature distributions at square-kilometre (km<sup>2</sup>) spatial resolution and hourly temporal resolution. These outputs are regarded as directly relevant for identifying urban/extra-urban hot spots and supporting targeted heatwave risk/impact management measures, particularly in relation to urban planning and design decisions. In the case of SLZ, the **analysis is initially conducted at the federal state level**, adopting a broader spatial perspective to support a first understanding of emerging heat-related health risk. However, **hotspot identification would be particularly relevant at the urban scale**, especially for the city of Salzburg, which is not the primary focus of ICARIA within this application. No specific adaptation measures are currently modelled within this scenario. According to the experts, the **ICARIA DSS only partially supports the modelling workflow required for the heatwave event-tree scenario** during the replication phase across all modelling components (“elementary bricks”). This partial workflow support limits the operational maturity of the system in its present configuration, directly informing **RQ-Sci2** with regard to the practical ease of application, and contributing to **RQ-Sci4** by clarifying the current level of functional integration compared to conventional urban heatwave risk/impact assessment approaches.

With respect to replication effort and resource implications, the main cost drivers are associated with (i) input data acquisition, harmonisation, and processing, (ii) personnel time required for framework configuration and modelling activities, and (iii) calibration and validation tasks across hazards, exposure/vulnerabilities, risk/impact, and resilience pathways. **The overall cost required to replicate the ICARIA modelling framework is estimated at €20,000–50,000**, with a typical **implementation time of at least 3 months**. The most time-consuming steps include data collection and preparation. The principal obstacle identified as potentially delaying replication or increasing costs is the limited availability of vulnerability curves describing population responses to heat exposure. These findings provide structured evidence addressing **RQ-Sci2**, particularly in relation to the economic, temporal, and organisational feasibility of applying the heatwave modelling workflow in new contexts.

### 4.2.3. Wildfire impact and adaptation: modelling implementation

#### Risk assessment methodology

The **wildfire risk assessment for the Salzburg Region follows the same methodology adopted in the AMB CS**. The analysis was performed using the DSS. To ensure consistency and comparability across the project, the SLZ CS adopts SSP1-2.6 and SSP5-8.5, as well as the following temporal periods:

- 1919 - 2020 (historical period)
- 2015–2040
- 2041–2070
- 2071–2100

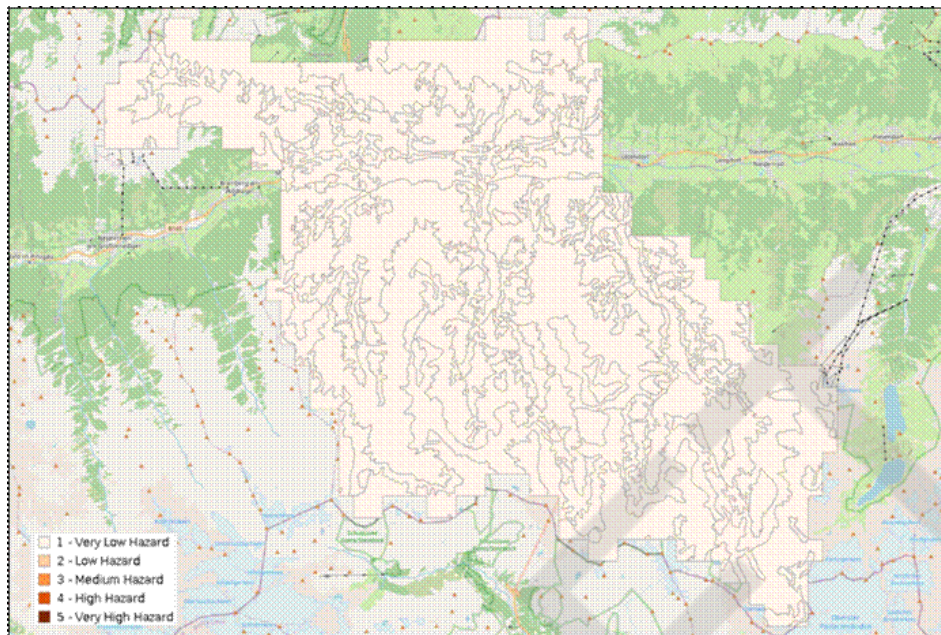
Following the established workflow, **exposure data were integrated using the Corine Land Cover 2018 dataset** to define land use categories within the area of interest. Hazard data were processed in shapefile format, focusing on the FWI as the main indicator of wildfire probability.

#### Hazard assessment results

Although the assessment framework remains identical to that applied in the AMB CS, the **hazard thresholds were adjusted to reflect the specific climatic conditions of the SLZ**.

Preliminary analysis indicated that FWI values in Salzburg do not exceed the standard DSS threshold of FWI>50, which is typically used to identify extreme wildfire conditions. To enable a meaningful risk assessment within the platform, the **threshold for extreme events was therefore recalibrated to FWI>40**. It should be noted that lowering this threshold may lead to a slight overestimation of the resulting risk levels within the DSS; however, this adjustment ensures that potential wildfire threats remain detectable within the analysis.

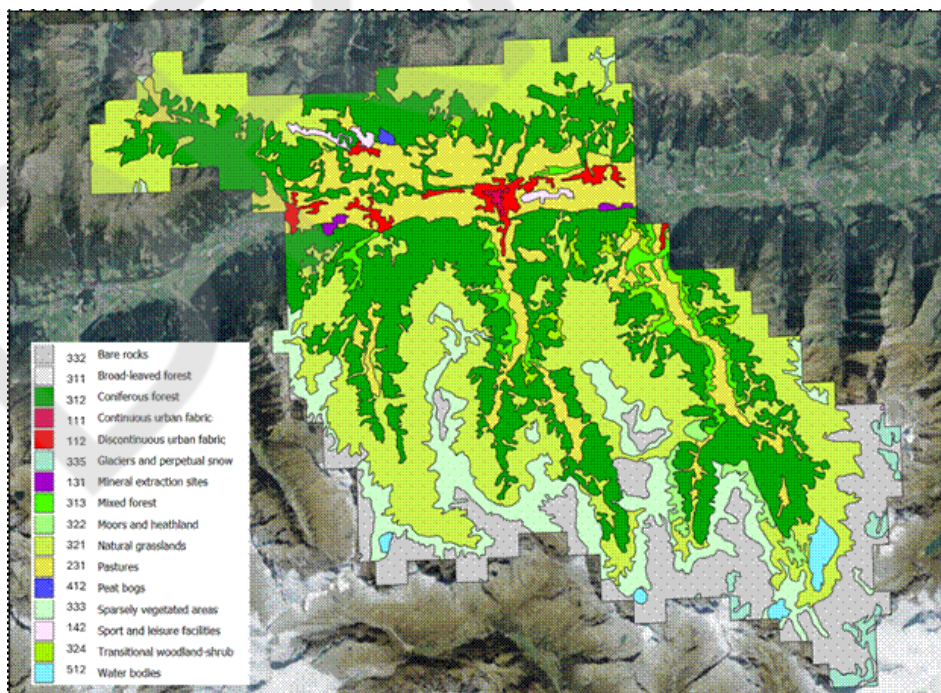
Consistent with the findings in the AMB CS, projections for SLZ indicate a progressive development of hazard across future time periods. Within the DSS, hazard levels are standardised on a scale from 1 to 5, based on the frequency of days exceeding the defined FWI thresholds. For **SLZ CS, the results indicate a hazard level of 1 across the entire study area**, as illustrated in Figure 65.



**Figure 65.** Hazard map for wildfires in the SLZ CS created with the DSS.

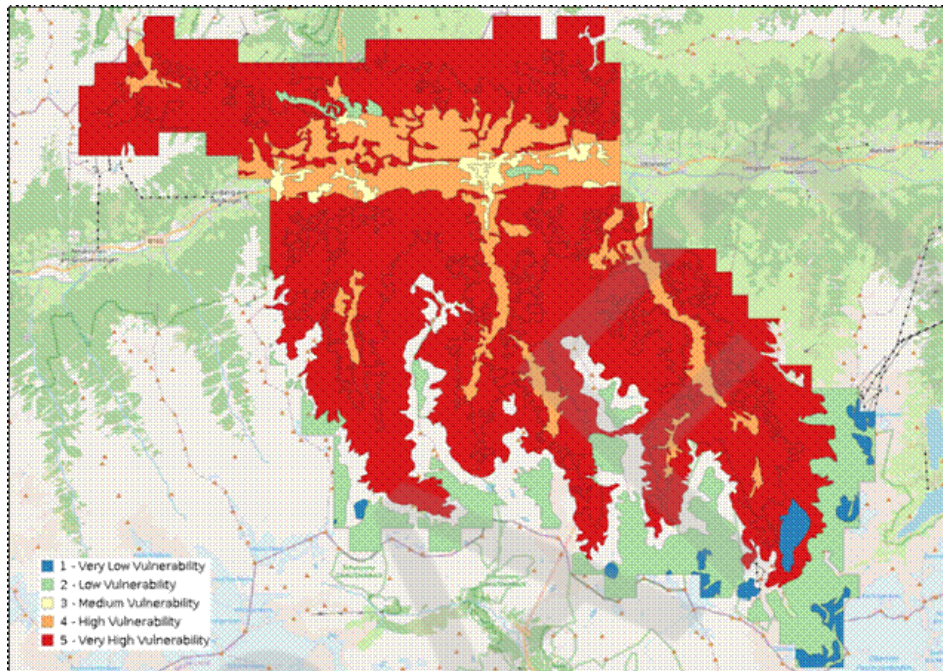
Exposure and vulnerability assessment

**Exposure is derived from the Corine Land Cover** dataset (Figure 66), which provides standardised information on land use within the study area. The areas included within the SLZ encompass different land-use classes, namely artificial surfaces, agricultural areas, forests and semi-natural areas, wetlands, and water bodies.



**Figure 66.** Corine Land Cover map of the SLZ CS.

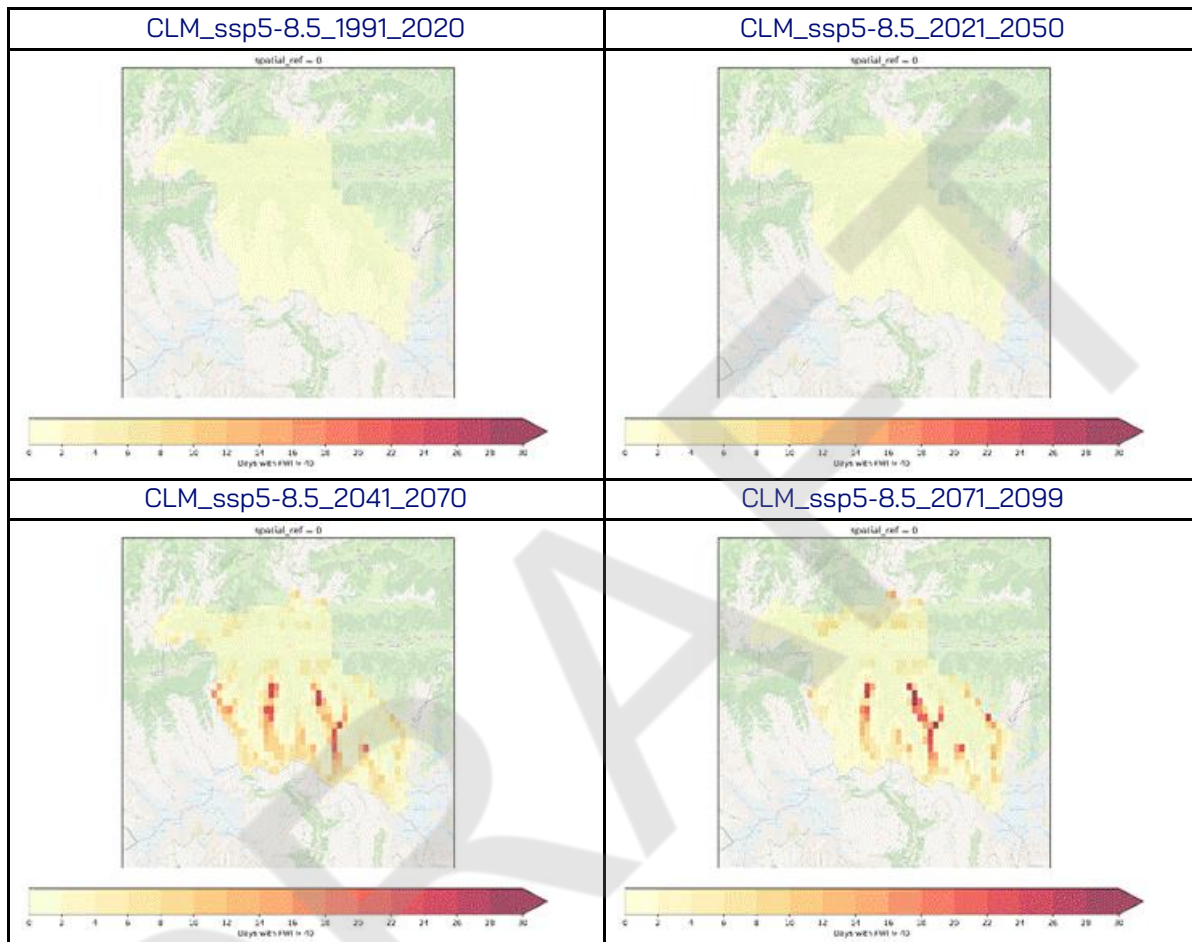
Once the Corine Land Cover dataset was processed, the DSS assigned a **vulnerability score ranging from 1 to 5 according to land use classification**. High vulnerability was attributed to forest and agricultural areas, Medium to High vulnerability to artificial (urban/built-up) surfaces, and Very Low vulnerability to wetlands and water bodies. The outcomes of this analysis were subsequently represented in a vulnerability map (Figure 67).



**Figure 67.** Vulnerability map of the SLZ created with the DSS.

Impact assessment results

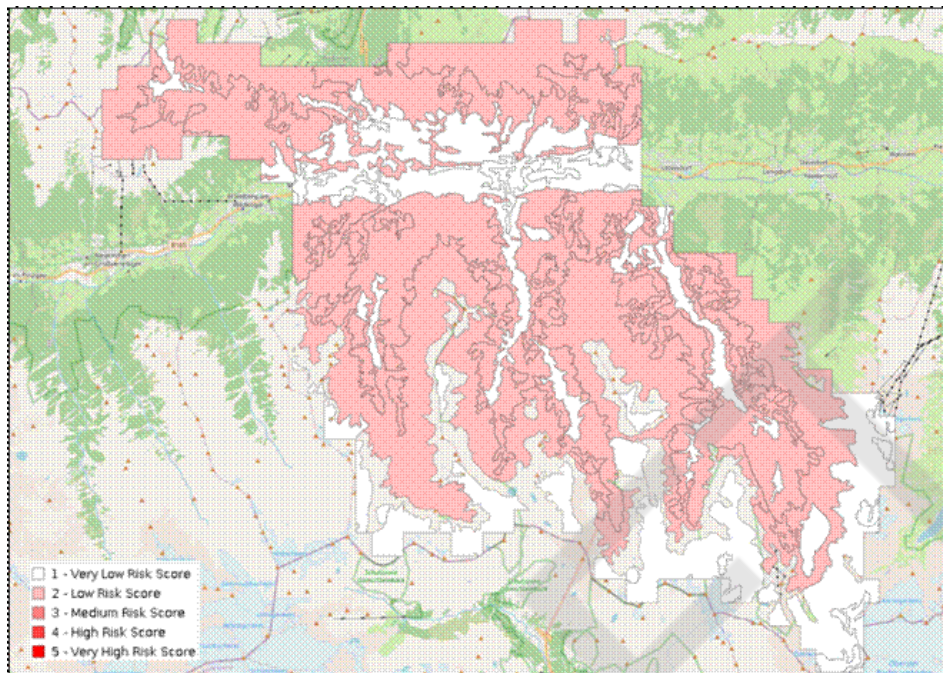
Similar to the results obtained in the AMB CS, the **wildfire impact assessment for the SLZ showed no significant variation across the analysed scenarios** (Figure 68).



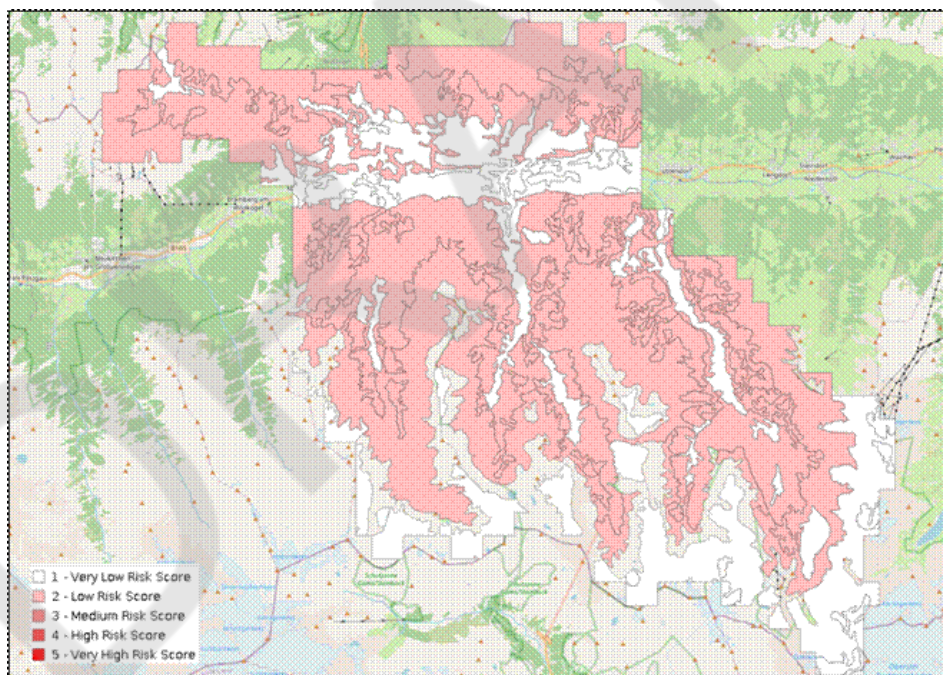
**Figure 68.** Hazard map comparison for the SLZ CS.

As shown in Figure 68, no days with  $FWI > 40$  were recorded during the historical period. In the most distant future scenarios, most of the study area falls within the 0-15 days threshold. However, in the most exposed areas, the number of days exceeding  $FWI > 40$  reaches 27 days in the period 2041–2070 and 36 days in the period 2071–2099.

Figures 69 and 70 show that there is **no substantial increase in anticipated impacts between historical conditions and future projections.**



**Figure 69.** Risk map of wildfires for the SLZ CS, historic period.

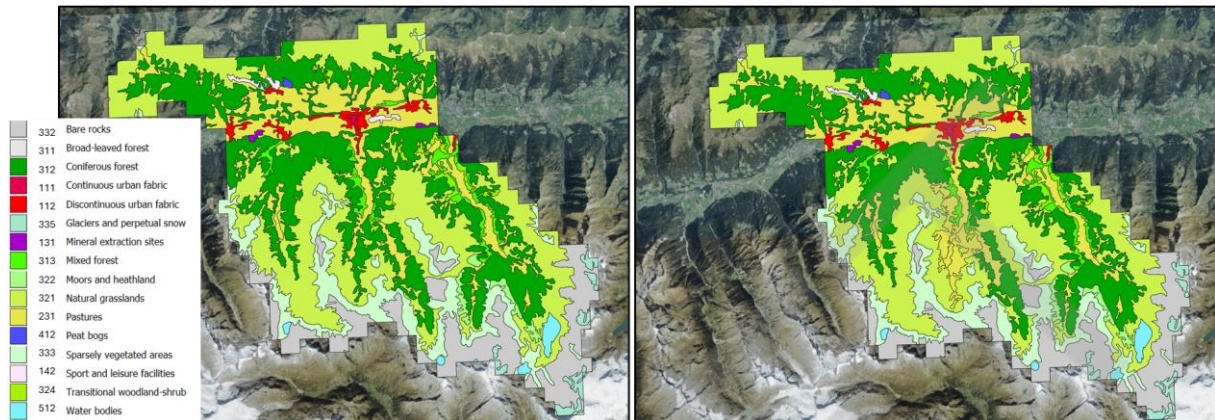


**Figure 70.** Risk map of wildfires for the SLZ CS, SSP5-8.5, 2041-2070 period.

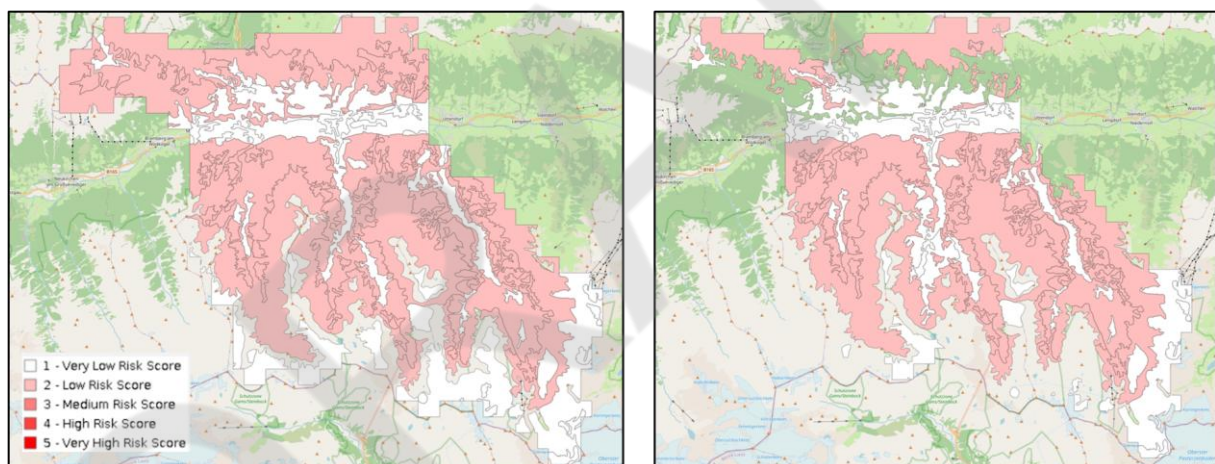
Adaptation scenario

In the SLZ adaptation scenario, specific land use changes were implemented by **converting selected coniferous forest areas into pastures**. This strategy serves a dual purpose: physically, it creates natural fuel breaks that reduce the high fire load associated with dense coniferous stands, thereby lowering the overall vulnerability of the landscape. Socioeconomically, this measure strengthens local

agriculture and food sovereignty. By promoting grazing and open pasture management, the region not only enhances its wildfire resilience but also secures sustainable land use that supports the local economy and maintains traditional cultural landscapes. Figure 71 shows the new adaptation land use map, while Figure 72 shows the related risk/impact map.



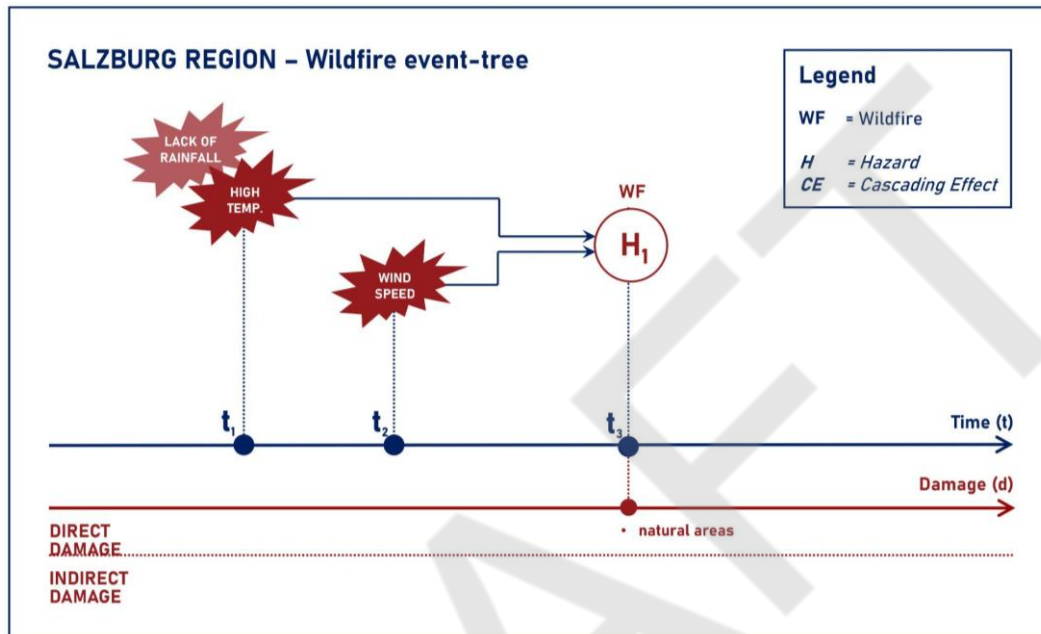
**Figure 71.** Land use map of the SLZ CS: left, current condition (2018); right, adaptation involving the conversion of forest areas into pasture.



**Figure 72.** Wildfire risk/impact for the SLZ CS under the SSP5-8.5 scenario (2041-2071): left, current condition (2018); right, adaptation involving the conversion of forest areas into pasture.

#### 4.2.4. Wildfire impact and adaptation: expert-based insights

The wildfire Mini-trial for the SLZ CS is based on a single-hazard event-tree scenario representing the temporal sequence of processes and impacts associated with wildfire events (Figure 73).



**Figure 73.** Wildfire event-tree scenario for SLZ Mini-trial (replication phase).

The triggering conditions include a prolonged lack of rainfall and high temperatures ( $t_1$ ), combined with wind speed ( $t_2$ ), creating a favourable setting for fire ignition, which is assumed to result from human-related sources (e.g., discarded cigarettes). Wildfires then emerge as the main hazard ( $t_3$ ), causing direct short-term damage to natural areas ( $t_3$ ). The sequence of events (triggering conditions and main hazard) reflects a rapid-onset impact pathway, in which impacts materialise shortly after fire ignition. Impacts include loss of vegetated/semi-vegetated areas, with limited cascading effects beyond the areas directly affected by the fire.

Within this targeted event-tree scenario, the **ICARIA modelling framework is considered applicable primarily at the local scale and over temporal horizons limited to days**. The modelling process behind hazard and impact assessment is based on the FWI, derived from basic climate variables. Exposure information for assets at risk can be obtained from publicly available data repositories. In this context, the **performance of the ICARIA modelling framework is expected to be largely dependent on the quality and spatial resolution of the input datasets**. Taken together, these aspects support the internal coherence and methodological robustness of the wildfire modelling workflow, thereby informing **RQ-Sci1** regarding the scientific plausibility and reliability of the modelling results.

From a data requirements and technical constraints perspective, the **effort required to prepare input data for replication is assessed as moderate**, reflecting harmonisation and preprocessing needs before the modelling process. The availability and quality of hazard and exposure/vulnerability

parameters are considered key factors influencing successful replication in other contexts. The main data-related barriers are associated with insufficient documentation or metadata, as well as missing mandatory variables (e.g., limited observed damage), which may hinder data integration and harmonisation across contexts. These elements highlight the sensitivity of the modelling configuration to contextual data conditions and calibration requirements, contributing to **RQ-Sci3** by identifying areas where further methodological refinement may be needed, while also positively informing the technical feasibility dimension of **RQ-Sci2**.

Considering the expected outputs, the replication of the wildfire Mini-trial is anticipated to generate fire risk maps providing spatially explicit risk scores at a spatial resolution of 4 km<sup>2</sup>. These outputs are directly relevant for assessing wildfire exposure and supporting targeted wildfire risk/impact management measures, particularly in the context of emergency preparedness and spatial planning. The adaptation measure considered within this scenario consists of changing land use, specifically involving the conversion of selected coniferous forest areas into pastures. This measure aims to reduce fuel load and landscape vulnerability by introducing natural fuel breaks, while also supporting local agricultural practices. According to the expert, the **ICARIA DSS fully supports the modelling workflow required for the wildfire event-tree scenario** during the replication phase across all modelling components ('elementary bricks'). This full workflow support reflects a high degree of operational maturity and system integration in its current configuration, directly informing **RQ-Sci2** with regard to the practical ease of application, and contributing to **RQ-Sci4** by demonstrating a functional level of integration comparable to conventional wildfire risk/impact assessment approaches.

With respect to replication effort and resource implications, the main cost driver is personnel time required for framework configuration and modelling activities. **The overall cost required to replicate the ICARIA modelling framework is estimated at less than €10,000**, with a typical **implementation timeframe of under 1 month**. The most time-consuming step is expected to be data collection and preparation. While data collection and preparation are expected to be the most time-consuming steps, no specific obstacles were identified as potentially delaying replication or increasing costs, as the modelling workflow is considered relatively simple and easily replicable. These findings provide structured evidence addressing **RQ-Sci2**, particularly in relation to the economic, temporal, and organisational feasibility of applying the wildfire modelling workflow in new contexts.

#### 4.2.5. Stakeholder-based insights on impact and adaptation across hazards in the SLZ case study

This section summarises the responses to the ICARIA questionnaire from the SLZ CoP-engaged stakeholders across Trials (ADVANCED VERSION) and Mini-trials (BASE VERSION), integrating interpretative insights with references to the project's research questions (i.e., RQ-Sci1-4 on scientific validity, RQ-Ex1-3 on usability, RQ-Acc1-4 on acceptance, RQ-Soc1-2 on socio-economic relevance, and RQ-Sus1-2 on sustainability), as outlined in the methodological Section 3.1.4.2. Responses from three key stakeholders – all local authorities (two regional, one municipal), represented by one decision-maker, one technical staff member and one planner, mostly with advanced expertise in climate change and disaster risk management – show cautious but generally positive interest in the

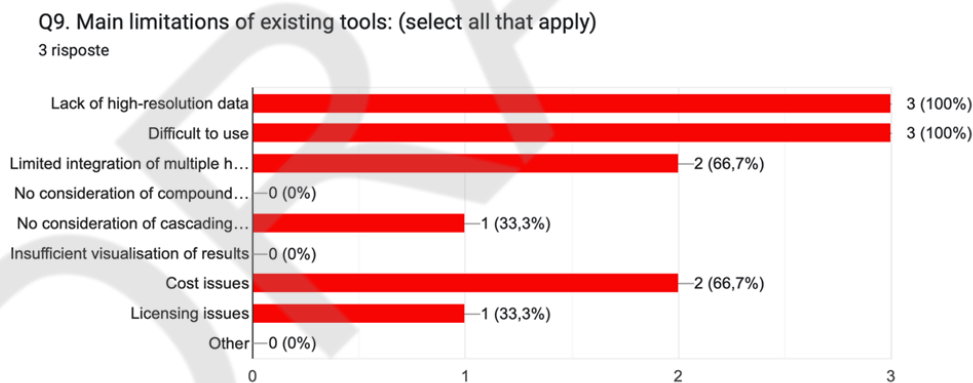
ICARIA tools, with higher appreciation for conceptual benefits than for practical feasibility and data robustness.

Respondent profile and Organisational needs and priorities

The SLZ sample includes one decision-maker, one technical staff member and one planner, all of whom have advanced expertise in climate change and disaster risk management. All three operate at regional or municipal scales and have experience of multiple hazards, including drought, heatwaves, wildfires, floods, storms, and compound events. The respondents periodically undertake climate risk or impact assessments (every 1-5 years), focusing on infrastructure safety, water management, land/ecosystem management, public health and civil protection. This context underpins a relatively high level of interest in enhanced, integrated risk/impact assessment tools, as well as a strong sensitivity to usability, data quality and resource demands.

Knowledge and use of existing risk/impact assessment tools

Despite having advanced or basic experience in climate risk management and conducting regular assessments, **SLZ respondents report not using digital tools or platforms for climate risk/impact assessment**. They identify **multiple limitations in the existing (mainly non-digital) tools or approaches they employ**, such as a **lack of high-resolution data, limited integration of multiple hazards, and no consideration of cascading effects**, as well as practical issues like **costs and licensing problems** (Figure 74).



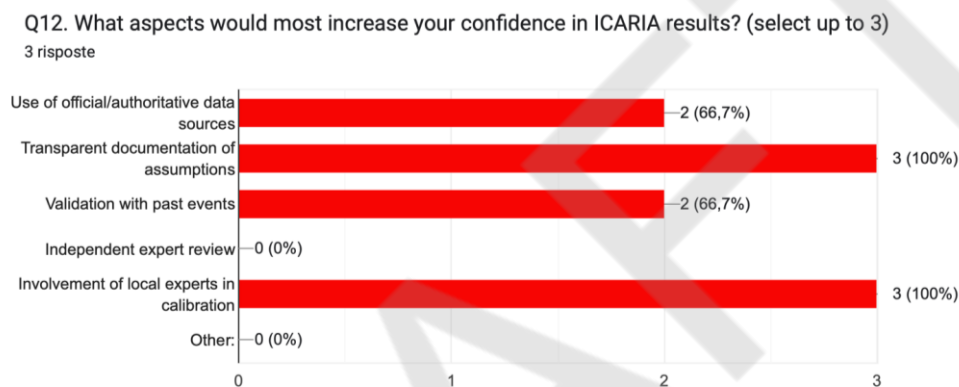
**Figure 74.** Distribution of SLZ stakeholder responses to Question 9 (Q9) of the questionnaire.

The unanimous emphasis on resolving data gaps and improving usability, as well as the lack of adoption of digital tools among respondents, positions **ICARIA as a potential upgrade in providing structured, multi-hazard risk/impact assessment capabilities tailored to local needs**. The value proposition centres on providing faster, more detailed overviews and better local adaptability.

Plausibility and reliability of ICARIA data and modelling results

Regarding the ICARIA modelling framework, respondents stress four key conditions for establishing trust in it: the use of official/authoritative data sources, transparent documentation of assumptions,

validation against past events, and the involvement of local experts in calibration (Figure 75). All three respondents judge the **input data used by ICARIA as “partly representative”** of their local context. This uniform response seems to underscore the shared perception that the **data used in the case study lacks the necessary granularity, specificity and/or calibration** to fully capture the heterogeneous geography, urban-rural mix, and compound hazard dynamics of SLZ. Qualitative comments reveal that **adaptability to local conditions is valued**, yet **current outputs are sometimes perceived as insufficiently traceable** or not clearly superior to existing approaches. Indeed, **SLZ stakeholders prioritise institutional legitimacy, methodological openness and participatory tailoring over purely technical refinements**, indicating that procedural trust is as critical as empirical validation for bridging the gap.



**Figure 75.** Distribution of SLZ stakeholder responses to Question 12 (Q12) of the questionnaire.

### Perceived Benefits and Use Cases

In terms of perceived benefits, one respondent (regional decision-maker) rates it as *“quite useful”* for their organisation/territory (e.g., urban planning, climate risk management, adaptation), while the other two respondents (regional technical staff and municipal planner) rate it as *“slightly useful”*. This seems to reflect institutional roles more than the actual benefits of using ICARIA: the decision-maker recognises its potential, likely in line with strategic priorities such as periodic assessments, whereas technical and planning roles are more reserved, possibly due to concerns about data and integration raised previously. Overall, the **benefits are considered concrete but incremental**. They support existing workflows and have a potential use in adaptation planning and infrastructure resilience, which underscores ICARIA's suitability for strategic, forward-looking tasks in local/regional settings where resources are limited.

### Cost Acceptability and Replication Feasibility

While the potential benefits of ICARIA are unanimously recognised, the stakeholders adopted different approaches regarding estimating costs and time for replication in other contexts. **The estimated replication cost of €20,000–50,000 for the ADVANCED VERSION (Trial) is considered acceptable only with co-funding or if the benefits are clearly demonstrated**. Cost components such as data acquisition/processing, technical development, staff time and maintenance are

generally ranked as only moderately acceptable, with at least one respondent perceiving replication as very high in technical complexity and unrealistic without a dedicated project. At the same time, there is a **conditional willingness to accept implementation times exceeding six months, provided intermediate outputs are delivered, and the results are of demonstrably high quality**. Replication is seen as technically demanding for both versions, often requiring specialised external expertise, which may limit autonomous uptake by local or regional administrations. Across both the ADVANCED VERSION and BASE VERSION, respondents converge on **several data- and model-related priorities**: finer resolution and better granularity of hazard maps, improved representation of exposure (i.e., assets, people, services), robust economic damage modelling, explicit treatment of cascading effects, and clearer communication of uncertainty. **Alignment with existing local indicators, standards and planning frameworks is consistently emphasised as being critical for real-world applicability and institutional acceptance**. Qualitative feedback stresses the need for traceable methods and convincing evidence of added value.

Interest in the DSS component

The **DSS component of ICARIA is generally perceived by the stakeholders as from “slightly” to “quite” valuable** for integrating modelling workflows into day-to-day operational and planning processes. Respondents indicate **conditional interest for adoption of the DSS as a standard tool**: one would adopt it after pilot testing, another only after full workflow support, and a third is more cautious, requesting real-time data integration or richer features before committing. The most useful workflow components include single- and multi-hazard assessment, exposure/vulnerability analysis, impact and economic damage estimation, cascading effects analysis, resilience assessment and adaptation option identification. Desired DSS enhancements include **real-time data integration, mobile/responsive interfaces, multi-user collaboration, custom scenario builders, and improvements in complete workflow coverage, the user interface, and local data integration**. These are often ranked among the top priorities for development (Figure 76).

Q41. Rank your top 3 priorities for DSS development/enhancement:

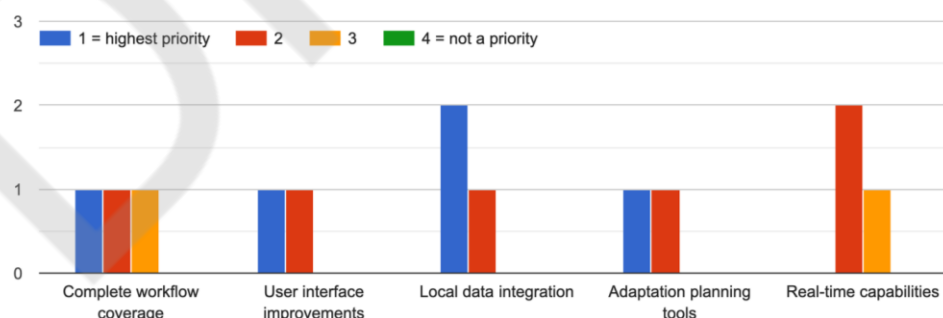


Figure 76. Distribution of SLZ stakeholder responses to Question 41 (Q41) of the questionnaire.

### Contributions, Socio-economic Impacts, and Ethics

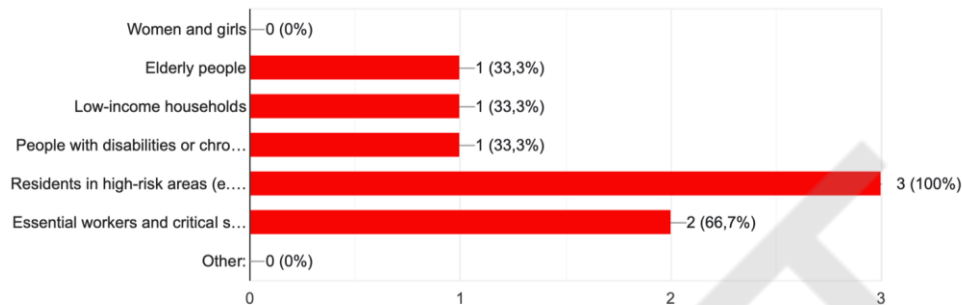
All three SLZ respondents anticipate **moderate positive socio-economic impacts** from using the ICARIA methods and tools in their territory. The most frequently cited impacts are better targeting of investments in resilient infrastructure (selected by all three respondents), improved transparency and accountability in planning (selected by all three respondents), support for local employment and economic development (selected by two respondents), and reduced economic losses from climate-related events (selected by two respondents). In view of these perceived positive socio-economic impacts and the need for local contribution to achieve better results, the respondents indicate that the most feasible contribution for their organisation would be to provide local data/access (the lack of which has also been noted earlier as one of the existing gaps of the framework) (RQ-Sus2) (Figure 77).



**Figure 77.** Distribution of SLZ stakeholder responses to Question 43 (Q43) of the questionnaire.

Additional impacts mentioned by the municipal planner include improved protection of vulnerable groups and neighbourhoods, indicating a recognition that ICARIA-informed decisions could enhance both economic efficiency and social resilience in hazard-prone areas. However, perceptions of **ICARIA’s potential to address gender and social equity issues** in climate risk management are mixed. The beneficiary groups most frequently identified include residents in high-risk areas (all three respondents), essential workers and critical services (two respondents), as well as elderly people, low-income households, and people with disabilities or chronic illnesses (one respondent) (Figure 78). This seems to suggest that while SLZ stakeholders associate ICARIA with benefits for spatially and socially vulnerable populations, they are uncertain about its capacity to explicitly operationalise gender-sensitive or equity-focused risk management without further customisation or complementary measures. Ethical concerns related to ICARIA use (e.g., data privacy, fairness) are downplayed in SLZ responses: two respondents answer “No”, and the third “Maybe”, with no follow-up specifications provided in Q49b. The limited articulation of concerns may originate from the early demonstration stage of the tools, where practical ethical risks have not yet been encountered, or from a focus on technical rather than normative dimensions. Nonetheless, the “Maybe” response indicates latent awareness that issues such as data handling, model fairness, and the equitable distribution of adaptation benefits could arise as the tools scale up. This highlights the need for proactive mitigation strategies, such as transparent data governance and participatory validation (RQ-Soc1-2).

Q48. In your view, which groups could benefit most from ICARIA-informed decisions? (select all that apply)  
3 risposte



**Figure 78.** Distribution of SLZ stakeholder responses to Question 48 (Q48) of the questionnaire.

#### 4.2.5.1. Responses specific to the ICARIA BASE VERSION (Mini-trials)

As outlined in Section 3.1.4.2, the ICARIA stakeholder questionnaire comprises two distinct sets of questions for the BASE VERSION (Mini-trials) and ADVANCED VERSION (Trials), reflecting their different methodological scope and replication requirements. The BASE one focuses on a streamlined, single-hazard configuration suitable for rapid deployment in data-sparse contexts, addressing usability, cost feasibility at lower technical thresholds, and operational applicability. In contrast, the ADVANCED one targets compound-hazard scenarios with cascading effects, emphasising more complex modelling requirements, extended timelines (e.g., >6 months), and enhanced analytical features (e.g., uncertainty representation). For the purpose of this deliverable, the responses presented here refer exclusively to the BASE VERSION and are structured around Mini-trials.

The SLZ Mini-trials are structured around key climate hazards, including heatwaves and wildfires, ensuring comprehensive hazard coverage in the assessment toolkit. Respondents were presented with a unified set of questions, addressing estimated replication costs, timelines, technical demands, data constraints, and improvement needs across all hazards (Table 15). This approach enabled stakeholders to evaluate the framework's transferability and scalability of the ICARIA framework within other contexts without hazard-specific prompting, thus capturing an integrated perspective of replicability.

**Table 15.** Key climate hazards included in SLZ Mini-trial and the effort required (costs and time) for replication in other contexts.

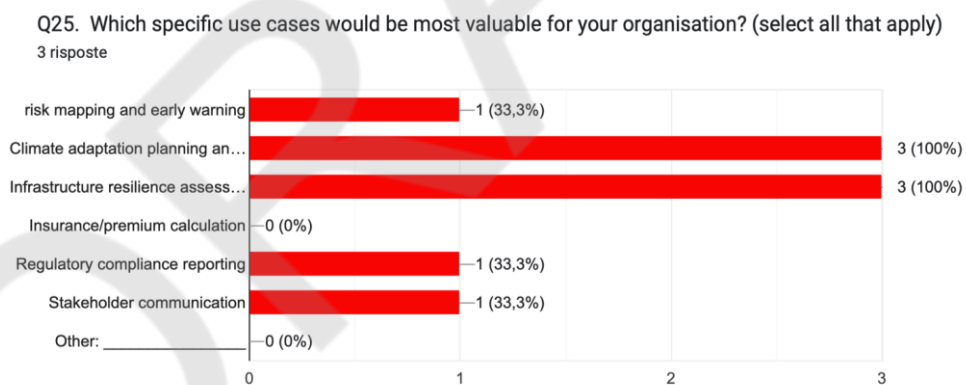
Effort required	Hazard	
	Heatwaves	Wildfires
Expected cost for replication (€)	10,000–20,000	<10,000
Expected time for replication	1-3 months	<1 month

Overall, the responses reveal a high degree of convergence among the three stakeholders, namely a decision-maker, a member of the technical staff, and a planner. This alignment reinforces the view of

the BASE VERSION as a single-hazard risk/impact assessment tool that can be deployed across multiple levels of governance, providing accessible entry points for practitioner-led use, while simultaneously highlighting constraints in terms of methodological sophistication and context-specific calibration.

### Perceived Utility and Application Domains

Perceptions of the **potential benefits of the BASE VERSION for the organisation/territory range from “slightly useful” to “quite useful”**. Respondents mainly associate its usefulness with supporting climate adaptation planning and design, as well as infrastructure resilience assessment, while also recognising its value for risk/impact mapping, early warning, stakeholder communication, and regulatory compliance reporting (Figure 79). This indicates that the **BASE VERSION is perceived not only as a technical modelling tool, but also as a planning and communication aid**. Its added value, however, appears to depend on improvements in data quality, localisation, and workflow integration. The most valued use cases for the BASE VERSION include single- and multi-hazard analysis and cascading effects, exposure and vulnerability mapping, risk/impact assessment (including economic damage), climate adaptation planning and design, as well as infrastructure resilience assessment. One respondent emphasises risk/impact mapping and early warning, as well as stakeholder communication, indicating the potential of the BASE VERSION to support dialogue with non-expert stakeholders and inform preparedness. Overall, this pattern suggests that **local and regional actors expect the BASE VERSION to provide an integrated overview of risks/impact across hazards and sectors, supporting strategic pathways** in addition to engineering design (RQ-Acc1).



**Figure 79.** Distribution of SLZ stakeholder responses to Question 25 (Q25) of the questionnaire.

### Comparative Performance and Strategic Value

When asked to compare the BASE VERSION to existing tools, one respondent explicitly notes that the results seem similar to those produced by other methods. This calls into question the **marginal added value of the BASE VERSION for highly specialised tasks**. However, open responses emphasise its **adaptability to local conditions and its capacity to provide a faster and more detailed overview of climate-related risks/impacts** (RQ-Sci4).

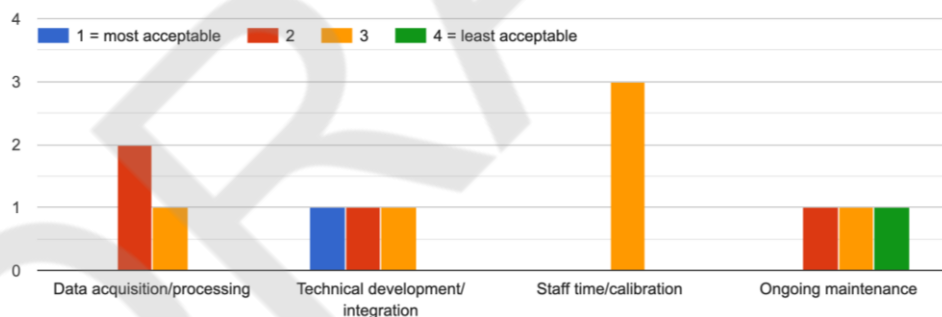
### Data Gap-Filling Methodologies

The main concerns regarding the **availability of data for the BASE VERSION centre on access to high-resolution spatial data, the capacity to represent key assets, populations and services**, as well as the challenge of aligning ICARIA datasets with existing local standards and indicators. One respondent also expresses concerns about the traceability and persuasiveness of results, implicitly linking data issues to **wider concerns about model transparency and interpretability**. These concerns suggest that the successful deployment of the BASE VERSION requires not only technical data integration but also co-design with local actors to ensure relevance and legitimacy (RQ-Sci1).

### Cost Acceptability and Replication Feasibility

Regarding the estimated efforts required to implement ICARIA in other contexts, respondents are cautiously optimistic. In terms of cost, for example, respondents describe the amounts (**€10,000–20,000 for heatwaves, and €<10,000 for wildfires**) as **“acceptable only with co-funding or external technical support”, or “acceptable only if the benefits are clearly substantiated”**. In terms of cost components, data acquisition/processing, technical development/integration, staff time/calibration, and ongoing maintenance generally fall within the mid-range, with ongoing maintenance occasionally being deemed the least acceptable. (Figure 80).

Q31. Rank the following cost components from most to least acceptable (1 = most acceptable; 4 = least acceptable):



**Figure 80.** Distribution of SLZ stakeholder responses to Question 31 (Q31) of the questionnaire.

This suggests that **financial feasibility will depend on external funding**, demonstrable returns and careful allocation of responsibilities between internal staff and external experts. The BASE VERSION is also considered to be technically challenging to replicate in new regions, with responses indicating **“moderate”, “high” or even “very high” technical complexity**. In some cases, replication is judged unrealistic without a dedicated project, highlighting limitations in internal capacity and the **need for sustained external support**. Nevertheless, there is some **openness to longer implementation times**, provided that intermediate outputs are made available and that the quality of results justifies the investment. (RQ-Sus2).

### 4.3. South Aegean Region CS – Naxos and Syros Islands

This section presents the Mini-trials developed for the SAR CS within Task 4.3. In line with the overarching objectives of the Mini-trials, the SAR activities address flood and extreme wind risk/impact modelling under climate change scenarios based on the SSPs framework (SSP1-2.6 and SSP5-8.5), respectively in the island of Naxos and in the island of Syros, with the dual aim of assessing transferability and replicability of the ICARIA methods and tools and evaluating the socio-economic implications arising from their implementation. The two hazard scenarios follow distinct design configurations: the **flood Mini-trial builds upon the Trial architecture developed from AMB CS and implemented within AMB and SLZ CS during the trial**, adapted and simplified to serve transferability and replicability purposes; the **extreme wind Mini-trial, by contrast, is implemented as stand-alone simplified assessments**, not directly derived from a prior Trial framework, and entail an explicit knowledge and approach transfer across CSs.

For each hazard type, Mini-trials describe the targeted event-tree scenarios, spatial and temporal scales of application, key input data requirements and modelling assumptions, as well as the main outputs relevant for decision-making and adaptation planning. In addition to presenting the modelling results, the following subsections integrate evidence derived from both expert and stakeholder questionnaires administered during the Mini-trial phase. This combined presentation of modelling outputs, expert-based technical assessment, and stakeholder-based evaluations provides a structured basis for addressing Task 4.3 purposes.

#### 4.3.1. Flood impact and adaptation: modelling implementation

##### Model Setup

The model is a **two-dimensional, raster-based overland-flow model implemented in the Landlab framework (I22)** (Hobley et al., 2017; Barnhart et al., 2020; Hutton et al., 2020) and driven by a temporally varying design storm. A **high-resolution Digital Elevation Model (DEM)** of the Sitia area is read from a GeoTIFF and used to construct a regular Landlab 'RasterModelGrid' with cell size  $d_{xy}$  and dimensions  $n_{rows} \times n_{cols}$ . DEM no-data cells are mapped to closed boundary nodes, so they do not participate in flow routing or overland-flow calculations.

**Artificial dam structures** are embedded directly in the DEM before the hydraulic simulation: dam centrelines from a polyline shapefile are buffered to a specified structural width, rasterised, and used to identify dam cells. For each dam, the crest elevation is set to the maximum existing ground elevation along the dam plus the prescribed dam height, and all cells within the dam polygon are raised to this crest, with a narrow transition zone generated via binary dilation and distance transforms to smooth the elevation from the original DEM to the dam crest.

Open boundaries are defined primarily by topography: cells at or below sea level are tagged as coastal nodes, and a thinned subset of these is set as fixed-stage boundaries to represent the coastline. In the absence of coastal cells, the lowest-elevation boundary node is designated as the outlet and assigned fixed-value conditions.

**Building footprints** from a polygon shapefile are rasterised to a binary mask; corresponding nodes are treated as closed (no-flow) obstacles, and their runoff coefficient is increased to near-impervious values. An optional polygon shapefile of initial water depth can be rasterised to prescribe pre-existing ponded water; if such data are unavailable, a small uniform initial depth of 0.001 m is applied only within rainfall-affected zones, while coastal nodes start dry.

The model is forced by a **time-variable rainfall** histogram provided as a CSV series of rainfall depths per 10-minute interval. This discrete hyetograph is converted into a continuous intensity function  $i(t)$  by linear interpolation and transformed to SI units, and the simulation length is set to the rainfall duration plus an additional three hours to capture flood recession. **Spatial variability in rainfall** is represented via a rainfall-zone polygon layer that is rasterised to a field of rainfall multipliers; if no such layer is available, a uniform multiplier of one is assumed.

Curve Number (CN) values from a land-use/soil shapefile are converted to dimensionless **runoff coefficients** (CN/100, constrained between 0.01 and 0.99) and rasterised to the computational grid, with building cells assigned nearly impervious coefficients. At each time step, for interior nodes within rainfall zones, the effective rainfall rate is computed as:

$$i_{eff} = i(t) \cdot m_{rain} \cdot C_r$$

Where:

$i_{eff}$  [L T<sup>-1</sup>] = effective rainfall contributing to surface runoff (applied as a vertical source term to the local water depth)

$i(t)$  [L T<sup>-1</sup>] = rainfall intensity as a function of time

$m_{rain}$  [-] = spatial rainfall multiplier

$C_r$  [-] = runoff coefficient

**Surface flow routing** is handled by Landlab's D8 'FlowAccumulator', which computes drainage directions and contributing areas over the modified DEM. **Flow accumulation** is calculated at the start of the simulation and can be updated periodically to remain consistent with evolving water surfaces.

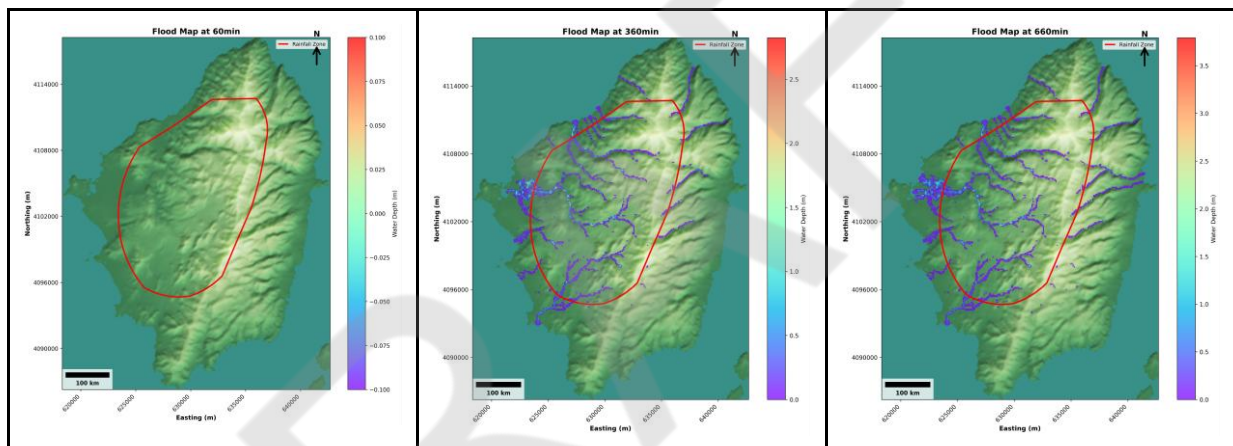
The **shallow-water dynamics of overland flow** are simulated using Landlab's 'OverlandFlow' component configured for steep slopes, which solves a simplified form of the shallow-water equations using a kinematic/diffusive wave approximation with Manning friction. A uniform Manning roughness of 0.03 and a weighting parameter  $\alpha = 0.7$  are adopted, representing mixed urban–peri-urban terrain with relatively steep gradients. The component updates water depth at core nodes in an explicit time-stepping scheme, while closed nodes (buildings, no-data) enforce no-flow conditions, and fixed-value nodes (coastline or outlet) represent stage-controlled boundaries.

Time integration uses an adaptive explicit time step  $\Delta t$  [T], computed internally by the OverlandFlow component, further constrained not to exceed 60 s and not to fall below 10<sup>-6</sup>s, and statistics of  $\Delta t$  (minimum, maximum, mean, variability) are recorded for later analysis. Numerical stability is monitored by checking each updated depth field for NaN, infinite, or negative values, and a counter of stability warnings is incremented when such anomalies occur.

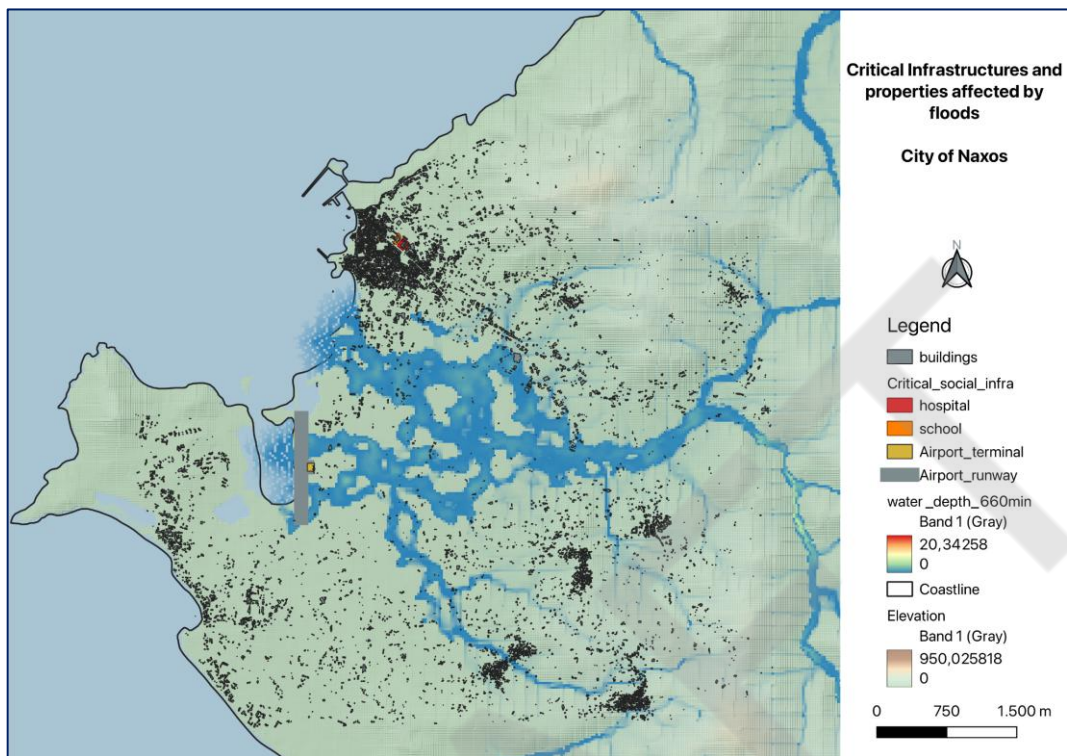
When rainfall begins, a “baseline” depth field is stored; subsequent outputs subtract this baseline and truncate negative values, so that reported flood depths represent rainfall-induced inundation rather than pre-existing water in depressions or coastal cells. A water mass balance is constructed by tracking total water volume on the grid (depth integrated over cell area) and cumulative rainfall input volume at each step, enabling quantification of retention and storage effects, including the influence of dams.

At user-defined intervals (typically every 10 minutes after rainfall onset), the model writes gridded GeoTIFF outputs of corrected water depth and water-surface elevation (DEM plus depth), as well as maps of flow accumulation, runoff coefficients, rainfall zones, building masks, dam locations, and initial/baseline depth fields, together with high-resolution visualization products that overlay flood depths on hillshaded terrain with buildings, rainfall polygons, and dam centerlines.

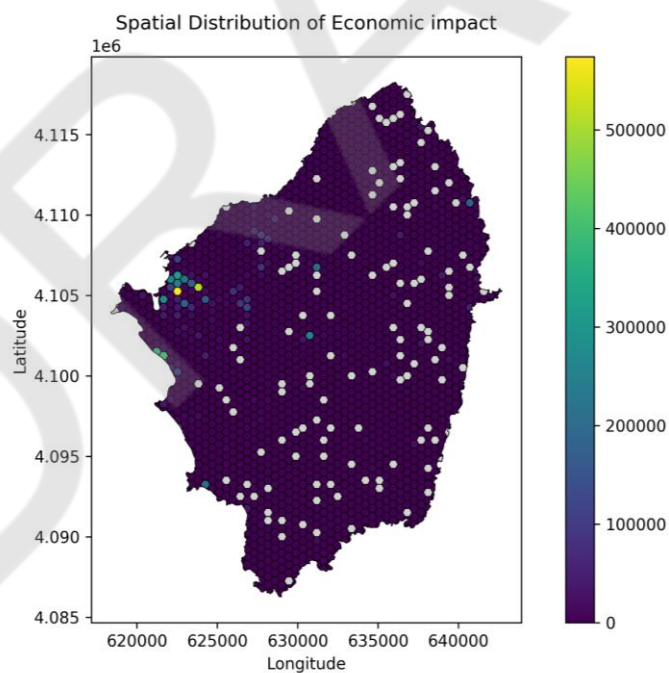
In the case of Naxos, the 50-year return period (R100) event was simulated, based on the climatic projections and the Ministry of Environment data, which is 600 mm in a period of 10 hours (Figures 81 and 82).



**Figure 81.** Flood evolution (left), rainfall starts (middle) after 6 hours of rainfall, and (right) after 10 hours when the rainfall stops, on the island of Naxos.



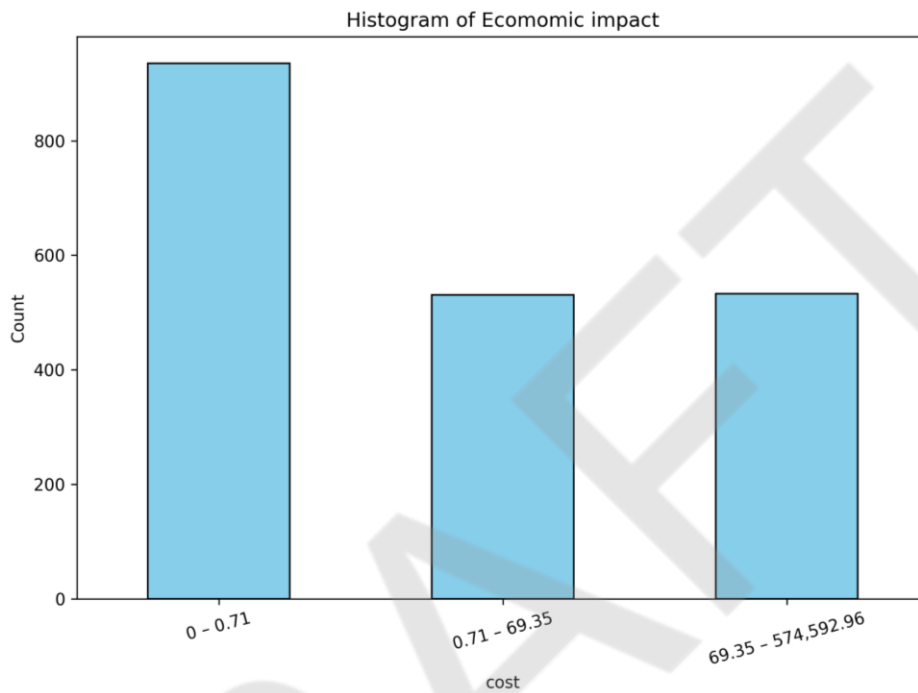
**Figure 82.** Critical infrastructures and properties affected by the R100 flood event on the island of Naxos.



**Figure 83.** Impact assessment map of CI and properties of the island of Naxos generated through the ICARIA DSS.

The impact assessment map (Figure 83), developed using ICARIA DSS, delineates the spatial distribution of economic impacts across the region. Most of the areas is shown in dark purple,

indicating negligible economic losses, consistent with the histogram (Figure 84). However, several highly localised hotspots of significant impact are evident (depicted by green and yellow hexagons, reaching values of approximately 550 units). These damages are concentrated in a cluster on the western edge of the study area, suggesting a localised vulnerability or the presence of high-value assets, including the city of Naxos, the hospital, and the airport.

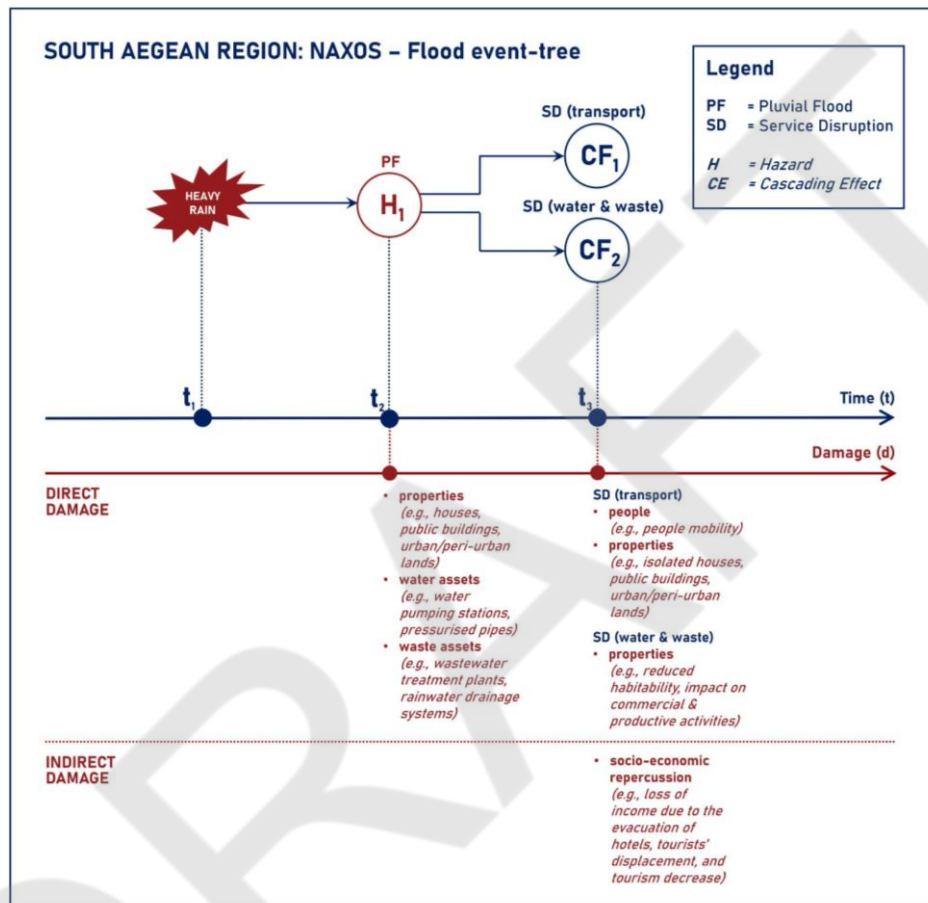


**Figure 84.** Bar chart showing the economic impact on CI and properties generated through the ICARIA DSS.

The histogram shows that economic damages are largely concentrated in the lowest range, with over 800 instances falling between €0 and €0.71. The moderate and high-impact categories occur with similar frequency, each comprising around 500 instances within the ranges of €0.71–€69.35 and €69.35–€574,592.96, respectively. This confirms that, while low-level impacts are widespread, severe damages are less frequent but disproportionately costly.

### 4.3.2. Flood impact and adaptation: expert-based insights

The **flood Mini-trial for the SAR CS**, specifically for Naxos Island, is structured around a single-hazard event-tree scenario representing the temporal sequence of processes and impacts associated with prolonged heavy rain (Figure 85).



**Figure 85.** Pluvial flood event-tree scenario for SAR Mini-trial, Naxos Island (replication phase).

The triggering event corresponds to prolonged heavy rainfall ( $t_1$ ), which progressively leads to soil saturation and a reduced capacity of surface/subsurface drainage systems, ultimately culminating in the occurrence of a pluvial flood event ( $t_2$ ). This causes direct short-term damage to properties and to water and wastewater assets ( $t_2$ ), as well as service disruption in transport, water distribution and wastewater management systems ( $t_3$ ), with additional socio-economic losses across multiple sectors, particularly in tourism ( $t_3$ ). The sequence of events (triggering event, main hazard, and related cascading effects representing further hazard development) shows a rapid-onset impact pathway in which impacts materialise shortly after the initial triggering conditions. Impacts include damage to buildings, as well as degradation and/or malfunctioning of the water distribution network (e.g., water pumping stations, pressurised pipes, etc.) and the sewer network (e.g., wastewater treatment plants, rainwater drainage systems, etc.). These impacts are accompanied by additional effects on both people (e.g., impaired mobility, including that of tourists) and properties (e.g., isolated houses, public buildings, and urban/peri-urban lands) resulting from disruptions to the transport system, as well as

further effects on properties (e.g., reduced habitability, impact on commercial and productive activities, etc.) resulting from disruptions to water distribution and wastewater management systems.

Within this targeted event-tree scenario, the **ICARIA modelling framework is therefore considered applicable at the local and regional scale and over temporal horizons of days**, in line with the gradual evolution of pluvial flood impacts. The modelling process behind pluvial flood hazard and impact assessment is based on a site-specific modelling configuration, which relies on long-term local datasets and focuses on the extreme event of the 50-year period. In particular, it is implemented through a two-dimensional raster-based overland-flow model built within the Landlab framework and driven by a temporally varying rainfall input. Flood dynamics are simulated using a high-resolution digital elevation model to represent terrain-controlled surface runoff, while land use and soil characteristics are incorporated through spatially distributed runoff coefficients derived from Curve Number values. In this context, the **performance of the ICARIA modelling framework is expected to be highly dependent on the quality and resolution of precipitation, topographic and land use datasets**. Taken together, all these aspects support the internal coherence and methodological robustness of the pluvial flood modelling workflow, thereby informing **RQ-Sci1** regarding the scientific plausibility and reliability of the modelling results.

From a data requirements and technical constraints perspective, the **effort required to prepare input data for replication is assessed as moderate**, reflecting harmonisation and preprocessing needs before the modelling process. The availability and quality of hazard and exposure/vulnerability parameters are considered key factors influencing successful replication in other contexts. The main data-related barriers are associated with restricted or proprietary access, limited temporal resolution, and outdated or inconsistent datasets, which may constrain data harmonisation and integration across contexts. These elements highlight the sensitivity of the modelling configuration to contextual data conditions and calibration requirements, contributing to **RQ-Sci3** by identifying areas where further methodological refinement may be needed, while also informing the technical feasibility dimension of **RQ-Sci2**.

Considering expected outputs, the replication of the pluvial flood Mini-trial is anticipated to generate hazard maps of flooded areas resulting from a simulated 50-year return period rainfall event, at a spatial resolution of 25 m. In addition, property exposure maps identifying assets potentially affected by surface flooding are produced. These outputs provide a spatially explicit basis for targeted flood risk/impact management measures, particularly in the context of emergency preparedness and spatial planning. A potential adaptation measure considered within is the implementation of water retention dams at higher altitudes, aimed at reducing downstream runoff accumulation during intense rainfall events. According to the experts, the **ICARIA DSS fully supports the modelling workflow required for the pluvial flood event-tree scenario** during the replication phase across all modelling components (i.e., 'elementary bricks'). This full workflow support reflects a high degree of operational maturity and system integration in its current configuration, directly informing **RQ-Sci2** with regard to the practical ease of application, and contributing to **RQ-Sci4** by demonstrating a functional level of integration comparable to conventional pluvial flood risk/impact assessment approaches.

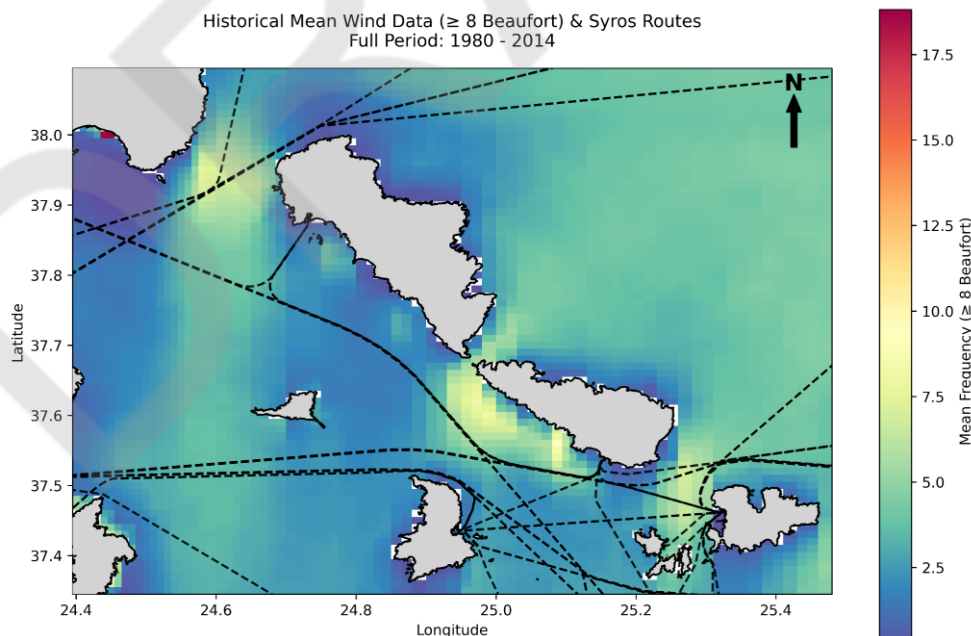
With respect to replication effort and resource implications, the main cost drivers are associated with (i) input data acquisition, harmonisation, and processing, (ii) personnel time required for framework

configuration and modelling activities, and (iii) development of the adaptation and resilience modules. **The overall cost required to replicate the ICARIA modelling framework is estimated at €10,000–20,000, with a typical implementation time of 3-6 months.** The most time-consuming steps include data collection and preparation, as well as harmonisation and preprocessing across multiple datasets and scales. Two main obstacles are identified as potentially delaying replication or increasing costs: the availability of climatic data and the lack of datasets with sufficiently high spatial resolution. These findings provide structured evidence addressing **RQ-Sci2**, particularly in relation to the economic, temporal and organisational feasibility of applying the pluvial flood modelling framework in new contexts.

### 4.3.3. Extreme wind impact and adaptation: modelling implementation

The modelling approach used to assess the **impact of extreme wind** focuses on the disruption of ship connections with the island of Syros and the closure of its main port. To assess this, the analysis is based on the downscaled COSMOS data (provided by AIT) with a spatial resolution of  $2 \times 2$  km. The threshold applied in this analysis derives from the national directive enforced by the coast guard, which restricts or prohibits passenger ships from departing from ports or following specific routes, and requires vessels already underway to seek safe ports. Based on this directive, the threshold corresponds to wind speeds exceeding 8 bf.

The analytical approach uses **downscaled COSMO data combined with the official shipping routes** linking the Port of Syros with the mainland and the rest of the islands. When wind speed exceeds the threshold along the shipping route, the methodology assumes complete service disruption. Figure 86 shows the spatial distribution of the mean number of days per year above the threshold of 8 bf for the historical period.



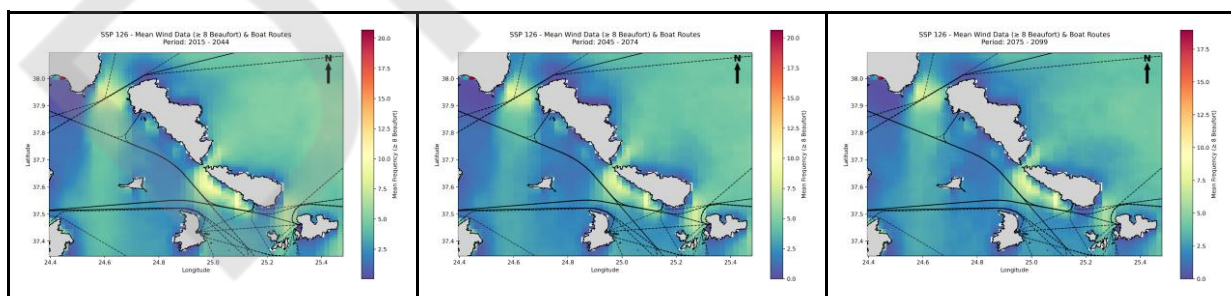
**Figure 86.** Map of the northern Cyclades showing the mean total annual days with wind speeds above 8 bf for the historical period.

The results of this methodology can be **validated using data provided by the CoP members, and more specifically by the Hellenic Coast Guard and the Port of Syros**. According to Table 16 showing the period 2020-2022, the port is closed approximately 9 days per year due to extreme winds.

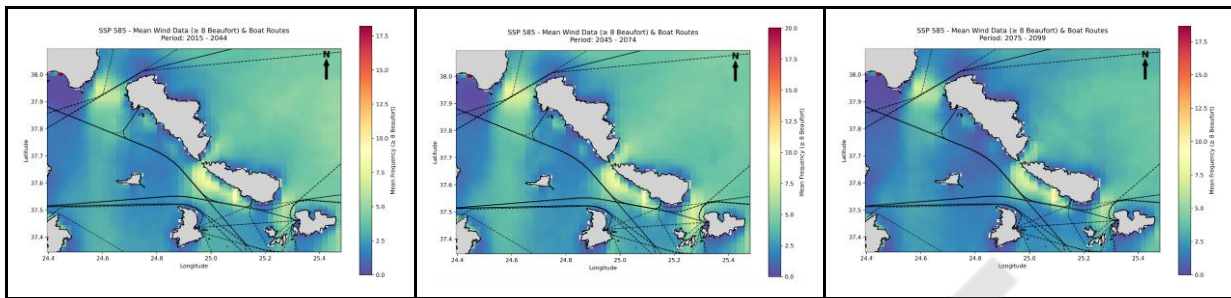
**Table 16.** Number of days per month the Port of Syros is closed due to extreme winds.

Port of Syros - Days of port service disruption			
Month	2020	2021	2022
January	5	1	3
February	0	3	4
March	1	1	0
April	2	1	0
May	0	0	0
June	0	0	0
July	0	0	0
August	0	0	0
September	0	0	1
October	0	0	2
November	1	1	0
December	0	1	1
<b>SUM</b>	<b>9</b>	<b>8</b>	<b>11</b>

Based on the methodology described above, the spatial distribution of the mean annual number of days with wind speeds exceeding the operational threshold is presented for both SSP1-2.5 and SSP5-8.5 scenarios in Figures 87 and 88. These conditions are used as a proxy for potential service disruption of the Port of Syros.



**Figure 87.** Maps of the northern Cyclades showing the mean total annual days with wind speeds above 8 bf for the SSP1-2.6 scenario.



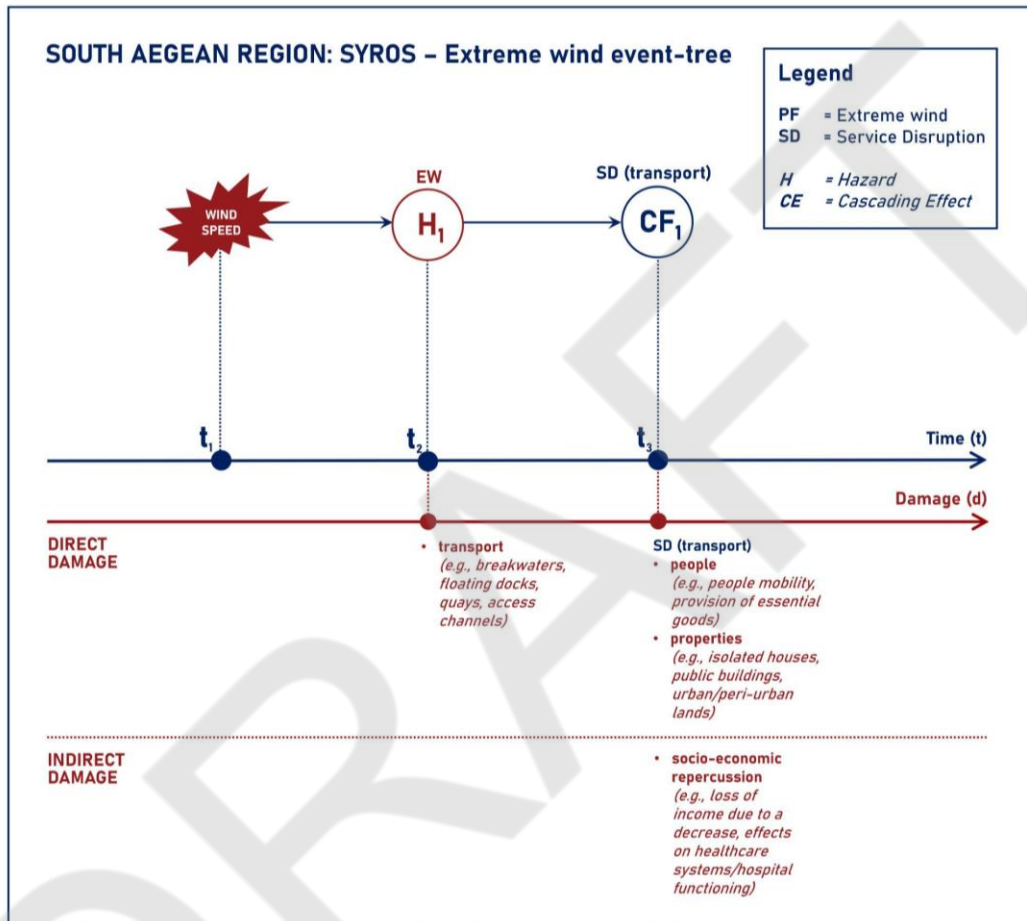
**Figure 88.** Maps of the northern Cyclades showing the mean total annual days with wind speeds above 8 bf for the SSP5-8.5 scenario.

The comparison between the historical period and the future scenarios shows little to no change in the mean number of days in a year with wind speeds exceeding 8bf. The main difference can be observed for the fat future (2074-2099), when a decrease in the number of days above threshold occurs in both scenarios.

DRAFT

#### 4.3.4. Extreme winds impact and adaptation: expert-based insights

The **extreme wind Mini-trial for the SAR CS**, specifically for Syros Island, is structured around a single-hazard event-tree scenario representing the temporal sequence of processes and impacts associated with prolonged high wind conditions (Figure 89).



**Figure 89.** Extreme wind event-tree scenario for SAR Mini-trial, Syros Island (replication phase).

The triggering event corresponds to a sustained increase in high speed ( $t_1$ ), which progressively leads to extreme wind conditions ( $t_2$ ). This results in direct short-term damage to transport assets ( $t_2$ ), and subsequent disruption to transport service ( $t_3$ ), with additional socio-economic losses across multiple sectors, particularly in tourism, as well as repercussions on the community well-being ( $t_3$ ). The sequence of events (triggering event, main hazard, and related cascading effects representing further hazard development) shows a rapid-onset impact pathway in which impacts materialise shortly after the initial triggering conditions. Impacts include degradation and/or malfunctioning of the transport network, particularly maritime infrastructure such as commercial and recreational ports (e.g., breakwaters, floating docks, quays, access channels, etc.). These impacts are accompanied by additional effects on both people (e.g., impaired mobility, including that of tourists, and disruptions in the supply of essential goods) and properties (e.g., isolated houses and public buildings such as hospitals) resulting from disruptions to the transport system.

Within this targeted event-tree scenario, the **ICARIA modelling framework is therefore considered applicable at the local and regional scale and over temporal horizons of days**, in line with the gradual evolution of extreme winds impacts. The modelling process behind extreme wind hazard and impact assessment is based on a site-specific modelling configuration relying on downscaled COSMOS datasets. The analysis focuses on wind conditions exceeding operational thresholds (i.e., 8 bf) defined by national maritime safety regulations enforced by the Hellenic Coast Guard. In particular, the modelling process evaluates the potential disruption of maritime transport services linking the Port of Syros with the mainland and neighbouring islands when wind speeds exceed this threshold. In this context, the **performance of the ICARIA modelling framework is expected to be highly dependent on the quality and resolution of the downscaled wind datasets**. Taken together, all these aspects support the internal coherence and methodological robustness of the extreme wind modelling workflow, thereby informing **RQ-Sci1** regarding the scientific plausibility and reliability of the modelling results.

From a data requirements and technical constraints perspective, the **effort required to prepare input data for replication is assessed as moderate**, reflecting harmonisation and preprocessing needs before the modelling process. The availability and quality of hazard and exposure/vulnerability parameters are considered key factors influencing successful replication in other contexts. The main data-related barriers are associated with restricted or proprietary access, limited temporal resolution, and outdated or inconsistent datasets, which may constrain data harmonisation and integration across contexts. These elements highlight the sensitivity of the modelling configuration to contextual data conditions and calibration requirements, contributing to **RQ-Sci3** by identifying areas where further methodological refinement may be needed, while also informing the technical feasibility dimension of **RQ-Sci2**.

Considering expected outputs, the replication of the extreme wind Mini-trial is anticipated to generate hazard maps representing wind speed, with a spatial resolution of 5 km or finer, and a maximum daily temporal resolution. In addition, exposure and vulnerability maps of port infrastructure are produced, identifying assets potentially affected by extreme wind conditions. These outputs provide a spatially explicit basis for targeted extreme wind risk/impact management measures, particularly in the context of emergency preparedness and spatial planning. A potential adaptation measure considered within this scenario consists of upgrading port infrastructure to improve the safety and operational resilience of vessel berthing under high-wind conditions. According to the experts, the **ICARIA DSS is reported not to support the full modelling workflow required for the extreme wind event-tree scenario** during the replication phase across all modelling components (i.e., 'elementary bricks'). This partial workflow support limits the operational maturity of the system in its current configuration, directly informing **RQ-Sci2** with regard to the practical ease of application, and contributing to **RQ-Sci4** in clarifying the present level of functional integration compared to conventional extreme wind risk/impact assessment approaches.

With respect to **replication effort and resource implications**, the main cost drivers are associated with (i) input data acquisition, harmonisation, and processing, (ii) personnel time required for framework configuration and modelling activities, and (iii) development of the adaptation and resilience modules. **The overall cost required to replicate the ICARIA modelling framework is estimated at €10,000–20,000**, with a typical **implementation time of 3-6 months**. The most time-

consuming steps include data collection and preparation, as well as harmonisation and preprocessing across multiple datasets and scales. Two main obstacles are identified as potentially delaying replication or increasing costs: the availability of climatic data and the lack of datasets with sufficiently high spatial resolution. These findings provide structured evidence addressing **RQ-Sci2**, particularly in relation to the economic, temporal and organisational feasibility of applying the extreme wind modelling framework in new contexts.

#### 4.3.5. Stakeholder-based insights on impact and adaptation across hazards in the SAR case study

This section summarises the responses to the ICARIA questionnaire from the SAR CoP-engaged stakeholders across Trials (ADVANCED VERSION) and Mini-trials (BASE VERSION), integrating interpretative insights with references to the project's research questions (i.e., RQ-Sci1-4 on scientific validity, RQ-Ex1-3 on usability, RQ-Acc1-4 on acceptance, RQ-Soc1-2 on socio-economic relevance, and RQ-Sus1-2 on sustainability), as outlined in the methodological Section 3.1.4.2. Responses from seven key stakeholders – mostly regional authorities, with a smaller representation of utilities – provide a targeted snapshot of potential ICARIA users within the targeted region.

##### Respondent profile and Organisational needs and priorities

The SAR sample is dominated by regional authorities (five out of seven respondents), with a smaller representation of a utilities company (one respondent) and a local/municipal authority (one respondent). The respondents typically hold technical, planning, or analytical roles: technical staff (three respondents), planners (two respondents), researcher/analyst (one respondent), and others (one respondent), indicating that answers reflect operational and expert perspectives rather than purely political views. Their geographical expertise is primarily regional, with some municipal and national scope. This aligns ICARIA with multi-level governance but with a clear emphasis on regional-scale decision-making.

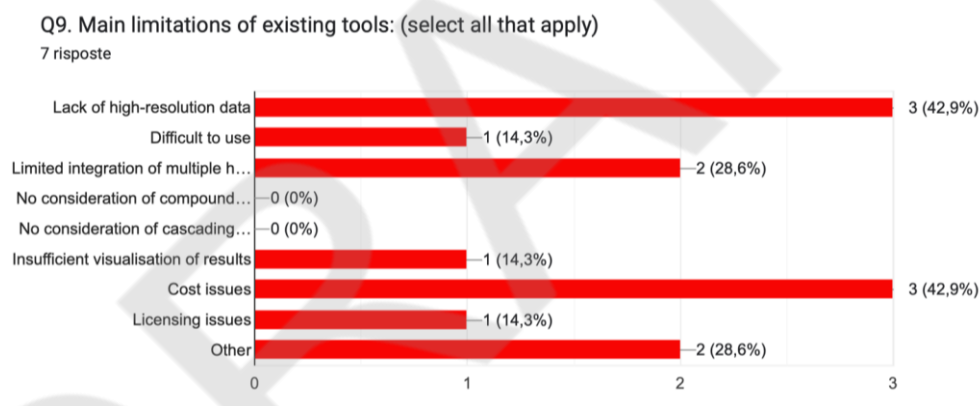
Experience in climate change and disaster risk management ranges from basic to advanced; however, the 'intermediate' and 'basic' levels prevail, suggesting a knowledgeable yet heterogeneous user base that may require differentiated capacity-building. The main climate-related hazards reported experience include droughts, heatwaves, wildfires, storms/extreme winds, floods, and compound events, confirming that ICARIA's multi-hazard and cascading focus is directly relevant to the sampled stakeholders' risk/impact landscape. Sectoral priorities tend to cluster around infrastructure safety, water and energy systems, mobility and transport, public health, ecosystems and land management, urban planning, and civil protection. This suggests that ICARIA is expected to support both critical infrastructure protection and broader territorial planning, rather than niche or purely academic use cases.

##### Knowledge and use of existing risk/impact assessment tools

Experience in climate change and disaster risk management is mostly "*basic*" (5/7, 71%), with one "*intermediate*" and one "*advanced*" level. Despite this, the assessment frequency is active: three out of seven conduct climate risk/impact assessments every year, two every 2–5 years, one only when

envisaged, and one does not know. This suggests that the user base has regular but not necessarily sophisticated routines. **Most respondents report that they do not currently use sophisticated digital platforms dedicated to climate risk/impact assessment, or that they rely on fragmented tools with limited integration and functionality.** Where tools are used, they are often specialised (e.g., drones for monitoring) or focused on single hazards, with limited interoperability across sectors and hazards. The **main limitations of existing tools** are consistently identified as: **lack of high-resolution data, cost and licensing issues, insufficient visualisation of results, and limited integration of multiple hazards and impacts.**

**Concerns about data quality and representativeness** are also explicit. Respondents emphasise the need for higher spatial resolution, better representation of exposures (i.e., assets, people, services), and improved treatment of cascading effects, as well as economic damage modelling and uncertainty communication (i.e., bands, intervals, scenarios) (Figure 90). Several respondents highlight the **importance of alignment with existing indicators and standards as a critical condition for effective adoption.** Regarding data availability, respondents anticipate challenges in terms of local-scale observational coverage and access to detailed critical-asset information, particularly in island and coastal settings. These concerns directly influence their expectations regarding the feasibility of replication and emphasise the importance of cooperating with local data owners and operators.



**Figure 90.** Distribution of SAR stakeholder responses to Question 9 (Q9) of the questionnaire.

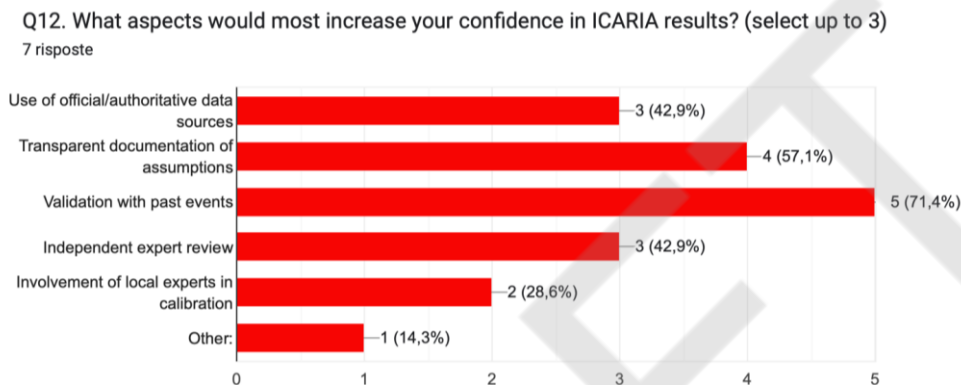
#### Plausibility and reliability of ICARIA data and modelling results

Overall, the **perceived credibility of ICARIA’s hazard and risk/impact maps is rated “high” to “very high”**, with input data generally considered mostly or fully representative of local conditions. This credibility is strongly linked to the use of official/authoritative data sources, transparent documentation of assumptions, validation with past events, independent expert review, and involvement of local experts in calibration (Figure 91).

**Respondents generally consider the ICARIA modelling framework to be “very useful”, with some “quite useful” (two respondents) and “slightly useful” (one respondent),** for supporting urban planning, climate adaptation planning and design, infrastructure resilience assessment, risk/impact mapping and early warning, regulatory compliance reporting, insurance/premium calculation, and stakeholder communication. Compared with existing tools, **ICARIA is anticipated to mostly perform**

**“significantly better”, though a few expect similar performance, which indicates a perceived but not universal step-change.**

The main added value expressed is ICARIA’s integrated, asset-level, multi-hazard, and future-looking approach, especially its capacity to model cascading effects and connect them to a DSS that helps prioritise sustainable and cost-effective adaptation measures. Respondents stress that **ICARIA transforms fragmented, single-hazard monitoring into a coherent framework that can support prioritised investments and operational decision-making.**



**Figure 91.** Distribution of SAR stakeholder responses to Question 12 (Q12) of the questionnaire.

#### Perceived Benefits and Use Cases

Four of the seven respondents rate the ICARIA modelling framework as *“very useful”* for their organisation/territory (e.g., urban planning, climate risk management, adaptation), two as *“quite useful”*, and one as *“slightly useful”*. **SAR respondents consistently prioritise use cases that support strategic decision-making and regulatory processes, with climate adaptation planning and design emerging as the most valued application**, selected by six out of seven (86%). Infrastructure resilience assessment and flood risk/impact mapping with early warning follow closely, each endorsed by five respondents (71%), reflecting the territory's vulnerability to floods, wildfires and cascading disruptions in critical sectors like infrastructure safety and civil protection. Regulatory compliance reporting appeals to four respondents, while insurance/premium calculation and stakeholder communication each attract three, underscoring ICARIA's perceived utility in bridging scientific outputs to financial, administrative and communicative needs (RQ-Acc1).

#### Cost Acceptability and Replication Feasibility

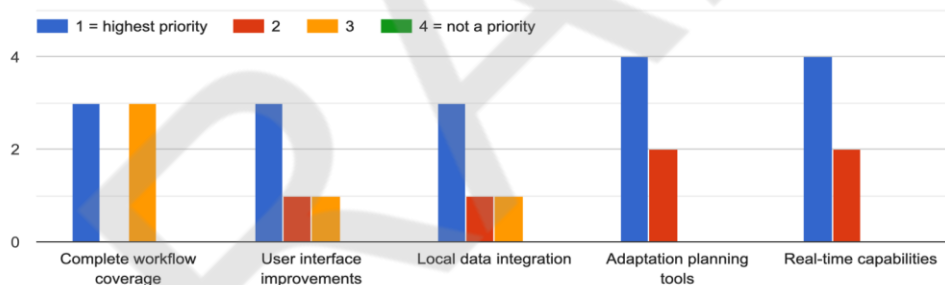
The **estimated investment of €10,000–20,000** to replicate the ICARIA framework in a new region is **generally seen as acceptable “if benefits are clear” by the majority of respondents or “acceptable only with co-funding or external technical support”**. When asked to rank cost components, respondents tended to rate data acquisition/processing, technical development/integration, staff time/calibration, and ongoing maintenance as “most acceptable” costs for many cases, especially when framed within clear benefits. In terms of **technical demands, the replication of ICARIA is perceived as moderate to high**. Several respondents indicate that replication would require specialised external expertise or that it would be unrealistic without a

dedicated project, while others foresee moderate demands with some external support. The majority express **willingness to wait 3–6 months for results, but often with the condition of receiving intermediate outputs to maintain engagement and support decision cycles.**

Interest in the DSS component

The **DSS is widely perceived as “very valuable” (four) or “quite valuable” (three respondents)** for integrating the ICARIA workflow into daily operational and planning processes. Respondents highlight key DSS-supported workflow components such as multi-hazard assessment (including compound coincident/consecutive events), exposure and vulnerability analysis, impact and economic damage estimation, cascading effects analysis, resilience assessment (i.e., RAF/RAT metrics), and adaptation-measure identification and assessment. **Adoption preferences vary:** some organisations would adopt the DSS immediately, others only after pilot testing, and some only once the full workflow is supported and stable. **Desired features include real-time data integration, adaptation planning tools, multi-user collaboration, and local data integration** (Figure 92). Many respondents also stress the **need for user-friendly interfaces and complete workflow coverage**, ranking these along with **local data integration and adaptation-planning tools as the highest priorities for DSS development.**

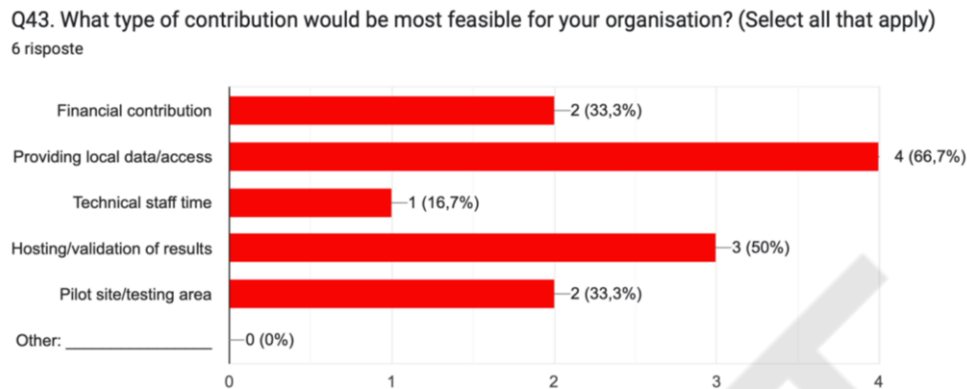
Q41. Rank your top 3 priorities for DSS development/enhancement:



**Figure 92.** Distribution of SAR stakeholder responses to Question 41 (Q41) of the questionnaire.

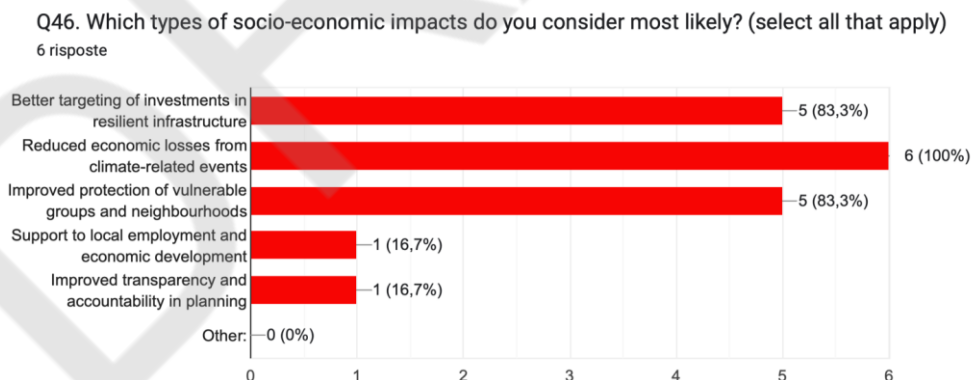
Contributions, Socio-economic Impacts, and Ethics

In terms of feasible contributions to ICARIA's development and replication, **SAR respondents emphasise non-monetary support, favouring providing local data or access as the most recurrent option.** Respondents delineate a range of practical contributions their organisations could extend to ICARIA, with providing local data or access featuring prominently across all six non-null responses. Two regional authority representatives pair this with financial contributions, while another combines it with hosting and validation of results, and a further response extends to both hosting/validation and serving as a pilot site or testing area. One respondent highlights technical staff time alongside a pilot site role, and a single entry specifies hosting/validation of results in isolation. These selections illustrate a disposition towards data-sharing, infrastructural support and validation-oriented engagement, with financial and personnel inputs appearing selectively (RQ-Sus2) (Figure 93).



**Figure 93.** Distribution of SAR stakeholder responses to Question 43 (Q43) of the questionnaire.

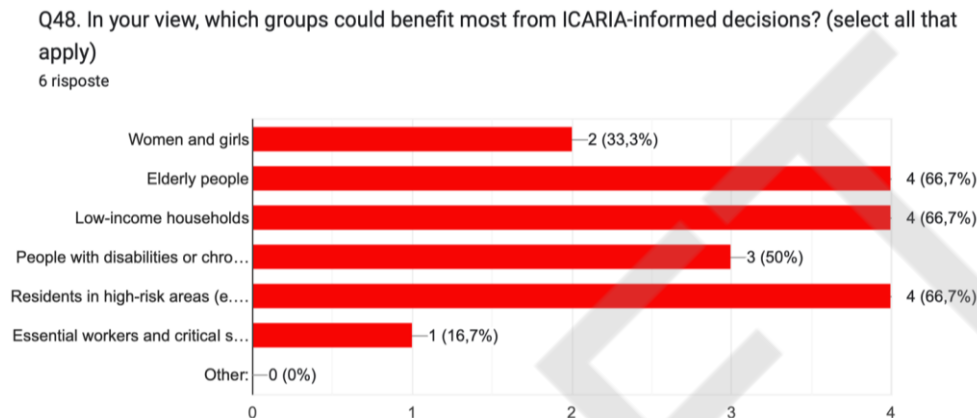
Respondents generally expect that using ICARIA could generate **high or very high positive socio-economic impacts**, particularly by improving the targeting of investments in resilient infrastructure, reducing economic losses from climate-related events, improving protection of vulnerable groups and neighbourhoods, supporting local employment and economic development, and enhancing transparency and accountability in planning. A few responses indicate only moderate or marginal impacts, reflecting more cautious expectations or contexts with constrained implementation capacity. Among the expected socio-economic impacts, reduced economic losses from climate-related events seem to be the most expected by all respondents, while improved protection of vulnerable groups and neighbourhoods recurs in five. Support for local employment and economic development accompanies one comprehensive listing, and improved transparency and accountability in planning appear in another. One response pair reduced economic losses and vulnerable group protection alone, illustrating the centrality of these core impacts alongside investment optimisation (RQ-Soc1-2) (Figure 94).



**Figure 94.** Distribution of SAR stakeholder responses to Question 46 (Q46) of the questionnaire.

Regarding **gender and social equity**, several respondents believe that ICARIA could help to address these issues, while others are more reserved, indicating “*somewhat*” or “*only marginally*”, or remaining uncertain. According to SAR stakeholders, the groups considered most likely to benefit from ICARIA-informed decisions are women and girls, elderly people, low-income households, people with

disabilities or chronic illnesses, residents in high-risk areas, and essential workers and critical services, rather than SLZ and AMB respondents. Ethical concerns such as data privacy, fairness, and distribution of benefits and burdens are generally not viewed as major obstacles, although some respondents flag potential issues that would need mitigation through careful governance and transparency mechanisms (Figure 95).



**Figure 95.** Distribution of SAR stakeholder responses to Question 48 (Q48) of the questionnaire.

#### 4.3.5.1. Responses specific to the ICARIA BASE VERSION (Mini-trials)

As outlined in Section 3.1.4.2, the ICARIA stakeholder questionnaire comprises two distinct sets of questions for the BASE VERSION (Mini-trials) and ADVANCED VERSION (Trials), reflecting their different methodological scope and replication requirements. The BASE one focuses on a streamlined, single-hazard configuration suitable for rapid deployment in data-sparse contexts, addressing usability, cost feasibility at lower technical thresholds, and operational applicability. In contrast, the ADVANCED one targets compound-hazard scenarios with cascading effects, emphasising more complex modelling requirements, extended timelines (e.g., >6 months), and enhanced analytical features (e.g., uncertainty representation). For the purpose of this deliverable, the responses presented here refer exclusively to the BASE VERSION and are structured around Mini-trials.

The SAR Mini-trials are structured around two climate hazards, including flooding and extreme winds, ensuring comprehensive hazard coverage in the assessment toolkit. Respondents were presented with a unified set of questions, addressing estimated replication costs, timelines, technical demands, data constraints, and improvement needs across all hazards (Table 17). This approach enabled stakeholders to evaluate the transferability and scalability of the ICARIA framework within other contexts without hazard-specific prompting, thus capturing an integrated perspective of replicability.

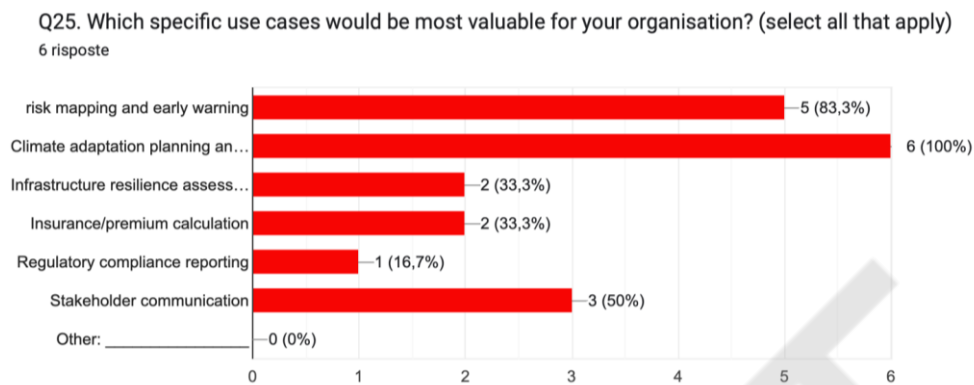
**Table 17.** Key climate hazards included in SAR Mini-trial and the effort required (costs and time) for replication in other contexts.

Effort required	Hazard	
	Flooding	Extreme winds
Expected cost for replication (€)	10,000–20,000	10,000–20,000
Expected time for replication	3-6 months	3-6 months

The responses from the SAR sample show substantial alignment across the seven stakeholders (including five regional authorities, a representation of a utilities company, and a local/municipal authority), demonstrating broad consensus. This uniformity positions the BASE VERSION as an efficient, single-hazard assessment tool adaptable to diverse administrative scales and resource-limited contexts, facilitating practitioner-driven deployment, yet revealing gaps in analytical rigour and site-specific adjustments.

#### Perceived Utility and Application Domains

The BASE VERSION is perceived as *“highly useful”*, with six respondents rating it *“very useful”* for concrete benefits in urban planning, climate risk management, and adaptation (one respondent *“slightly useful”*) with a coherent profile of priority applications for the BASE VERSION, dominated by an orientation towards strategic planning and operational communication, with marked convergence on two core elements: risk/impact mapping and early warning, and climate adaptation planning and design. Stakeholder communication features in three responses, alongside risk/impact mapping and adaptation planning, suggesting that the **BASE VERSION is perceived not merely as a technical instrument but as a facilitator of inter-institutional dialogue among regional authorities, municipalities, and critical service operators (e.g., water, energy, transport)**. Infrastructure resilience assessment, selected in two instances, indicates a focus on resilience evaluations for priority assets in island/coastal contexts where service continuity is paramount. Insurance/premium calculation and regulatory compliance reporting emerge sporadically (17% each), confined to more specialised responses (e.g., researchers/analysts). This configuration of **priorities appears strategic and communicative rather than purely modellistic and seems to underscore the BASE VERSION suitability for resource-constrained settings, to support annual or regulatory decision cycles** without demanding advanced modelling expertise (RQ-Acc1) (Figure 96).



**Figure 96.** Distribution of SAR stakeholder responses to Question 25 (Q25) of the questionnaire.

### Comparative Performance and Strategic Value

**Related to existing tools, the SAR stakeholders envision the BASE VERSION to perform "significantly better" (three respondents), "somewhat better" (two respondents), or with "similar performance" (one respondent),** with one incomplete. Strategic value lies in its integrated, future-oriented, asset-level multi-hazard approach, enabling prioritised adaptation even in simplified form. This predominantly positive assessment builds on the absence of dedicated digital platforms currently used by the respondents and the limitations in current approaches (mostly data resolution, multi-hazard integration), framing **BASE VERSION as a substantive upgrade for integrated, future-oriented risk/impact assessment.** The analysis of the open responses emphasises, in fact, ICARIA's capacity to deliver *"an integrated, future-looking, asset-level multi-hazard framework (including compound event/cascading effects) with DSS support for prioritising sustainable and cost-effective adaptation measures"*. One respondent highlights its role in transforming *"fragmented, single-hazard monitoring into [...] decision-support"* under extreme climate scenarios, while others note added value in regulatory compliance and stakeholder engagement. These narratives align with RQ-Sci4, portraying the BASE VERSION as a versatile enabler that transcends baseline deficiencies, particularly for adaptation planning and resilience in SAR's hazard landscape (RQ-Sci4).

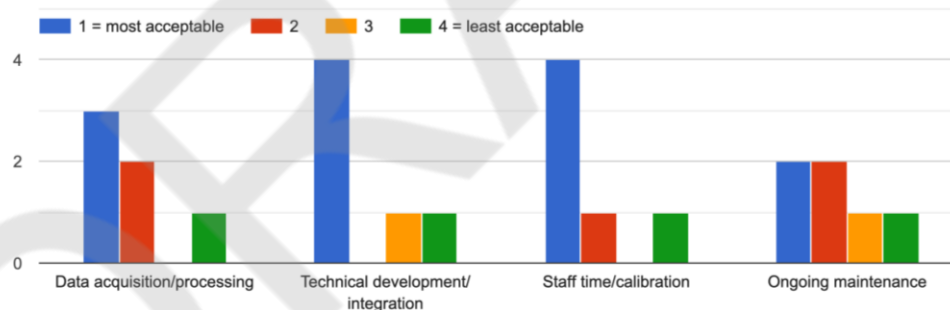
### Data Gap-Filling Methodologies

**Input data for BASE VERSION is deemed "fully representative" (three respondents) or "mostly representative" (two respondents), with gaps primarily in local observational coverage and critical-asset details** (one explicit concern). Confidence enhancers include official sources and local calibration, implying methodologies filling high-resolution exposure gaps would bolster plausibility. Satisfaction with data gap-filling methods (i.e., proxies, assumptions, interpolations) in both Trials and Mini-trials (ADVANCED VERSION/BASE VERSION) is uniformly neutral, with all recorded responses selecting *"Neither satisfied nor dissatisfied"*. BASE VERSION relies on accessible data proxies for gap-filling, but stakeholders stress validation and alignment with local standards to ensure reliability across hazards (RQ-Sci1).

### Cost Acceptability and Replication Feasibility

The **€10,000–20,000 replication cost is "acceptable if benefits clear" (four respondents) or "only with co-funding/support" (two respondents)**, with a nuanced hierarchy of acceptability for the four principal cost components associated with replicating the BASE VERSION, with predominance of data acquisition/processing and technical development/integration emerging as the most palatable. **Feasibility is "moderate" (three respondents), "high" (two respondents), "very high/unrealistic without project" (one respondents); timeline (3–6 months) accepted by six (conditional on quality/intermediates).** Cost components are mostly "1=most acceptable", but maintenance varies. The preference shown in the cost components aligns with SAR stakeholders' data-centric contributions and the perceived value of foundational investments in harmonising local inputs – such as asset inventories and sensor data – with ICARIA modelling workflows, thereby enhancing model localisation without excessive recurrent burden. Staff time/calibration mirrors this favourability, by four respondents. Ongoing maintenance, however, elicits more ambivalence, signalling wariness towards perpetual commitments, especially in settings where tool sustainability hinges on external partnerships or open-source architectures. The least acceptable responses given to assignment to data acquisition (one respondent), technical development (one respondent), staff time (one respondent) and maintenance (one respondent) underscore isolated pockets of concern, potentially linked to specialised roles (e.g., utilities) facing licensing/cost sensitivities (Figure 97).

Q31. Rank the following cost components from most to least acceptable (1 = most acceptable; 4 = least acceptable):



**Figure 97.** Distribution of SAR stakeholder responses to Question 31 (Q31) of the questionnaire.

Overall, these rankings – favouring upfront investments over enduring obligations – argue for a **replication strategy that minimises long-term operational expenditures through modular design, user training and co-funding**, thereby aligning with SAR's high enthusiasm for BASE VERSION benefits, while addressing feasibility barriers under RQ-Sus1/2 (RQ-Sus2).

## 5. Conclusions

The work carried out under **Task 4.3 represents a transition from performance validation to applicability validation**. While previous phases of the project have demonstrated the scientific robustness and technical capabilities of the ICARIA asset-level modelling framework, methods and tools, the Mini-trials have specifically explored the conditions under which these solutions can be transferred and replicated beyond the original implementation settings. In this context, the focus has shifted from assessing whether the solutions 'work' to understanding how, where, and at what cost/effort they can be effectively applied.

To this end, Mini-trials constitute a distinct validation layer to **assess the ICARIA approach under realistic implementation conditions**, including differences in data availability, modelling configurations, stakeholder expectations, required expertise, resource constraints, and levels of tool integration. They operated along two distinct configurations: **derived Mini-trials**, built upon existing Trial architectures and operationalised through the DSS, and **stand-alone Mini-trials**, implemented as independent simplified assessments entailing an explicit knowledge and approach transfer across CSs.

This has required a broader evaluation perspective, integrating technical feasibility with organisational, economic, and user-oriented considerations. The Mini-trials have therefore provided a structured environment to analyse the **adaptability of the modelling framework**, the **scalability of workflows**, and the **practical implications of implementation in heterogeneous contexts**. In doing so, they highlight that the value of ICARIA lies not only in its modelling capabilities but also in its potential to **support decision-making processes**, particularly when workflows are streamlined, appropriate supporting tools are available, and outputs are interpretable.

A key element of this phase has been the **combined use of expert judgement and stakeholder feedback**. These two perspectives are complementary: the former enables a detailed assessment of **technical and methodological constraints**, while the latter provides insight into **perceived usefulness, acceptability, and real-world applicability**. Their integration is essential to move beyond purely technical validation towards a more comprehensive understanding of implementation potential.

At the same time, it is important to acknowledge that the **Mini-trials were intentionally designed as targeted and resource-efficient activities**. This implies that some aspects of long-term adoption and institutional integration remain only partially explored and require further investigation in future exploitation, demonstration, and scaling activities beyond the project lifecycle.

### 5.1. Resolving the research questions

The results generated through the Mini-trials gain their full meaning when interpreted in relation to the **ICARIA RQs**, which provide the analytical framework underpinning both the Trial and Mini-trial phases. These research questions have been addressed through a **combination of modelling activities, expert-based assessments, and stakeholder feedback**. In this sense, their resolution

should be understood as the outcome of a cumulative validation process, in which different sources of evidence contribute to specific dimensions of the analysis.

In this context, the interpretation of the RQs focuses on **feasibility, implementation effort, and conditions for practical application**. The supporting evidence varies depending on the dimension considered. Questions related to scientific robustness and usability build primarily upon the extensive validation carried out during the Trials, while those related to transferability, replicability, and socio-economic impacts are further informed and enriched by the Mini-trial activities. As a result, the resolution of the RQs reflects complementary layers of evidence across different analytical dimensions.

From a methodological perspective, the evidence collected in Task 4.3 relies more strongly on structured expert judgement and perception-based stakeholder inputs. This has enabled the **identification of key enabling and limiting factors**, including data requirements, modelling complexity, resource needs, and institutional conditions influencing implementation, while also providing indicative insights into the potential for operational uptake of ICARIA solutions.

Despite these characteristics, the Mini-trials provide a sufficiently robust and coherent basis to interpret the RQs from a transferability-/replicability-oriented perspective, allowing the identification of key dependencies and boundary conditions influencing the potential uptake of ICARIA solutions elsewhere. The resulting level of resolution for each research question, integrating evidence from both Trials and Mini-trials, is summarised in Table 18 below.

**Table 18.** ICARIA research questions for the Mini-trials, and their mapped answers (below each question). The answers are based on methods described in Section 3.1.3.

RQ No.	Research Question
<b>RQ-Sci1</b>	How plausible/reliable are ICARIA data/modelling results?
<p>The plausibility and scientific robustness of ICARIA results are generally supported, building on the validation achieved during the Trials. The Mini-trials indicate that results remain plausible under transfer conditions, although with increased sensitivity to data quality, temporal/spatial resolution, and the use of proxy datasets. Expert feedback highlights the importance of calibration and data consistency, while stakeholder responses show that perceived reliability depends on transparency, validation against known events, and trust in input data.</p>	
<b>RQ-Sci2</b>	How easy/difficult/expensive would it be to apply the ICARIA solutions in new regions?
<p>The application of ICARIA solutions in new contexts is technically feasible but requires non-negligible effort. Expert assessments consistently identify data collection and harmonisation, model setup and calibration, and the need for specialised expertise as key cost and time drivers. The level of effort varies depending on data availability, modelling complexity, and DSS support. Stakeholder feedback confirms that feasibility is perceived as conditional, depending on available resources, institutional capacity, and external support.</p>	
<b>RQ-Sci3</b>	Which data/modelling aspects of ICARIA solutions need to be further developed/improved?
<p>The Mini-trials highlight several areas for improvement, primarily related to data harmonisation, handling of data gaps, and simplification of modelling workflows. Experts emphasise the need to operate under variable</p>	

data conditions, while maintaining robustness and consistency. Stakeholders further indicate the importance of clearer assumptions, improved transparency, and better alignment with locally available data. Overall, improvements should prioritise flexibility, scalability, and usability rather than increasing modelling complexity.

**RQ-Sci4**

To what extent does the functionality of the ICARIA tools go beyond the state of the art/what is currently used in the region?

ICARIA is generally perceived as extending beyond current practices, particularly in its ability to integrate multi-hazard and asset-level analyses. However, this added value is not uniform across contexts and depends on usability, transparency, and compatibility with existing tools and workflows. Expert feedback highlights methodological advances, while stakeholders emphasise practical applicability and ease of integration as key factors determining perceived added value.

**RQ-Ex1**

How easy or difficult is it to use the solutions?

Usability was largely validated during the Trials and is confirmed in the Mini-trials for expert users. However, the framework still requires a significant level of technical knowledge, and complexity remains a barrier for wider uptake. The evidence suggests that ICARIA can be effectively used by trained users, but additional simplification and support are needed to facilitate broader operational use.

**RQ-Ex2**

How easy or difficult is it to understand the results/recommendations offered by the solutions?

ICARIA results are generally considered meaningful and relevant, but their interpretation often requires technical expertise. Stakeholders indicate that clearer visualisation, improved communication of results, and better explanation of assumptions and uncertainties would enhance accessibility. The main issue is not the relevance of outputs, but their usability for non-expert users in decision-making contexts.

**RQ-Ex3**

What needs to be done to improve the user experience/usability of the solutions?

Key improvements concern workflow simplification, clearer user guidance, and stronger integration of modelling components within the DSS. Both expert and stakeholder feedback indicate the need for improved clarity of outputs, better communication of results, and more streamlined workflows. These aspects are consistently identified as important to improve usability and support broader uptake.

**RQ-Acc1**

How useful is the ICARIA methodology for the regional authorities and other stakeholders?

The ICARIA methodology is generally perceived as relevant for supporting climate risk-informed planning, particularly in multi-hazard contexts. Its usefulness increases when it is clearly aligned with local priorities and decision-making needs. Stakeholders emphasise that methodological relevance alone is not sufficient, and that practical applicability and institutional fit are key factors for adoption.

**RQ-Acc2**

How useful are ICARIA solutions for the Regional Authorities and other stakeholders?

ICARIA solutions are considered potentially useful for scenario analysis and adaptation planning. However, their practical usefulness depends on ease of use, integration into existing workflows, and clarity of outputs. Stakeholder responses indicate that usefulness is context-dependent and varies according to how well the solutions match operational needs.

**RQ-Acc3**

Do potential users want to use this type of solution in their work?

There is a general interest in adopting ICARIA solutions, but this remains conditional. Stakeholders express willingness to use the framework when complexity is manageable, costs are justified, and adequate support is available. Adoption is therefore not automatic, but depends on organisational capacity, perceived benefits, and alignment with existing practices.

**RQ-Acc4**

Which improvements/additional features would make the ICARIA methodology and/or solution(s) significantly more attractive for potential users?

Stakeholders identify several priorities to increase attractiveness, including improved usability, clearer outputs, better interoperability with existing tools, and stronger integration within the DSS. Additional needs include more guidance, simplified workflows, and clearer demonstrations of benefits. These factors are consistently highlighted as conditions for wider adoption.

**RQ-Soc1**

How much socio-economic impact (including gender and ethics issues) do Trial participants anticipate from ICARIA methodology and solutions?

The Mini-trials provide initial evidence that ICARIA solutions are expected to generate positive socio-economic impacts. Stakeholders associate these impacts mainly with improved risk awareness, more effective adaptation planning, and better decision-making. However, the magnitude of these impacts remains context-dependent and based on expectations rather than measured outcomes.

**RQ-Soc2**

What kind of socio-economic impacts (including gender and ethics issues) do Trial participants anticipate from the use of ICARIA methodology and solutions?

Expected impacts include reduced risks and losses, improved resilience of assets and services, enhanced planning capacity, and more informed policy-making. Stakeholders also highlight the importance of governance, equity, and the distribution of benefits. These aspects are considered relevant for the long-term acceptability and effectiveness of ICARIA solutions.

**RQ-Sus1**

Are potential users willing to pay for ICARIA solutions?

Willingness to pay for ICARIA solutions exists but is highly context-dependent. Stakeholders indicate that investment decisions depend on perceived added value, cost levels, availability of funding mechanisms, and institutional priorities. In several cases, financial support or co-funding is considered necessary to enable adoption.

**RQ-Sus2**

Are potential users willing to wait for ICARIA solutions to be tailored to other contexts?

Stakeholders show a certain tolerance for implementation timelines, provided that expected benefits are clear and relevant. However, long or uncertain timelines may reduce interest and hinder adoption. Acceptability of waiting time depends on the balance between expected value, urgency of needs, and confidence in the outcomes.

The results summarised above provide a consolidated view of how the ICARIA modelling framework performs when assessed through a transferability-/replicability-oriented lens.

Overall, the analysis confirms that the ICARIA framework maintains a **solid level of scientific robustness** when applied across different contexts, while highlighting a stronger sensitivity to contextual conditions. In particular, **data availability and quality, together with modelling assumptions and levels of simplification, emerge as key factors influencing the reliability and interpretability of results.**

A central finding concerns the effort required for replication. While the application of ICARIA solutions in new contexts is technically feasible, it is neither immediate nor trivial. The Mini-trials clearly indicate that **data collection and harmonisation, model setup and calibration, and the need for specialised expertise represent the main cost and time drivers**. Therefore, replicability emerges as a guided and resource-dependent process, rather than an automatic extension of transferability.

From a user perspective, the results confirm that **ICARIA solutions are perceived as relevant and potentially valuable for supporting risk-informed decision-making**, particularly in complex multi-hazard risk/impact contexts. At the same time, **usability and accessibility emerge as key challenges**. While expert users are generally able to operate the framework, broader adoption requires further simplification of workflows, clearer guidance, and improved communication of results.

The analysis also shows that adoption is not driven solely by technical performance. **Stakeholders' willingness to use and support ICARIA solutions depends on perceived added value, cost-effectiveness, compatibility with existing practices, and the availability of institutional and technical support**. In particular, willingness to invest and acceptable implementation timelines are shown to be highly context-dependent, confirming that sustainability is a critical dimension of replicability.

Importantly, the Mini-trials provide the first structured evidence on the socio-economic relevance of ICARIA solutions. Stakeholders consistently recognise their **potential to support more effective adaptation strategies, reduce risks/impacts, and improve planning capacity**. At the same time, the distribution of benefits, institutional feasibility, and long-term operational integration remain key aspects influencing their real-world impact.

Overall, the evidence collected supports the conclusion that ICARIA solutions have a concrete potential for application beyond the project, provided that key enabling conditions are addressed.

## 5.2. General conclusions

Deliverable 4.3 shows that the ICARIA asset-level modelling framework, methods, and tools can be extended beyond their original implementation settings, moving from a context-specific validation towards a more generalisable and scalable approach to climate risk/impact and resilience assessment.

The Mini-trials confirm that ICARIA provides a **flexible and modular modelling framework**, capable of being adapted to new geographical, hazard, risk/impact, and governance contexts. This adaptability represents a key strength, enabling the framework to operate across diverse CSs while maintaining methodological coherence.

At the same time, the results highlight that **transferability and replicability are not equivalent processes**, and that the two Mini-trial configurations reflect meaningfully different aspects of this distinction. In cases where existing Trial architectures provided a viable methodological basis, derived Mini-trials – enabled by the DSS, which offered a common modelling environment, consistent workflows, and the flexibility to recalibrate and reuse existing model components across contexts –

demonstrate that transferability can be pursued in a structured and operationally sustainable manner. In cases where no such basis existed, stand-alone Mini-trials evidence that achieving replicability demands considerably greater effort, encompassing the explicit transfer of knowledge and approaches across CSs, the adaptation of data inputs, and the realignment of modelling procedures with local institutional and operational conditions.

A key outcome of this deliverable is the identification of **enabling and limiting factors for replication**. Data availability and quality, modelling complexity, and the need for specialised expertise emerge as primary constraints. At the same time, the integration of modelling components within the ICARIA modelling framework and the support provided by the DSS can facilitate implementation, particularly when they contribute to more streamlined workflows and clearer outputs.

From a stakeholder perspective, the Mini-trials confirm the **high potential value of ICARIA solutions** in supporting decision-making processes related to climate risk/impact and adaptation planning. However, their adoption depends on several conditions, including usability, clarity of outputs, cost-effectiveness, and compatibility with existing practices. These findings indicate that replicability is not only a technical issue but also a matter of organisational capacity and institutional conditions.

The analysis also emphasises the importance of **socio-economic and sustainability dimensions**. ICARIA solutions are expected to contribute to reducing risks/impacts and improving resilience, but their long-term uptake depends on stakeholders' willingness to invest, acceptable implementation timelines, and the availability of resources and support mechanisms.

Overall, Deliverable 4.3 confirms that ICARIA provides a **transferable and adaptable approach** to climate risk/impact and resilience assessment, with concrete potential for application across different European contexts and beyond. At the same time, it highlights key priorities for further development, particularly in relation to modelling workflow simplification, enhanced user-friendliness, improved data handling procedures, and closer alignment with user needs. Taken together, these findings highlight that the added value of ICARIA lies not only in its modelling capabilities but in its ability to operate under varying data, resource, and institutional conditions, which ultimately shape its real-world applicability.

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## Annexes

### Annex A: Questionnaires for experts

**ICARIA project**  
*Expert Survey on Framework Replicability and Modelling Tools*

SECTION 1 – Case Study Facilitator profile

1. First Name and Last Name:  
\_\_\_\_\_

2. Organisation / Institution:  
\_\_\_\_\_

3. Professional role:  
\_\_\_\_\_

4. Field of expertise:  
\_\_\_\_\_

5. Main domain(s) of technical expertise:  
(Select all that apply)

Hazard modelling  
 Exposure / Vulnerability modelling  
 Impact / Risk modelling  
 Resilience assessment  
 Adaptation / Mitigation implementation  
 Climate or Environmental data  
 GIS / Geospatial analysis  
 Software development  
 Other (specify): \_\_\_\_\_

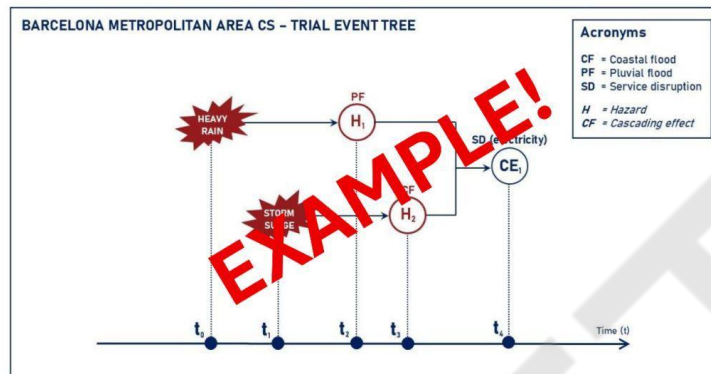
6. Familiarity with the ICARIA modelling framework:  
(Select a value from 0 to 5, where 0 = 'none' and 5 = 'very high')

0  1  2  3  4  5

SECTION 2 – Framework overview

7. Briefly describe the hazard/impact scenario modelled through the ICARIA framework:  
(Explain the scenario corresponding to the selected event-tree for the trial/mini-trial, paying attention to the temporal dimension which determines the relationship between hazards (whether compound coincident or compound consecutive), the impacted elements at risk and cascading effects considered.

1



Example response

The event-tree for the Barcelona Metropolitan Area TRIAL represents a **compound hazard scenario** driven by two initiating events occurring at different points in time:

- **Heavy rainfall** ( $t_0$ ), triggering **pluvial flooding** ( $H_1$  at  $t_2$ )
- **Storm surge** ( $t_1$ ), triggering **coastal flooding** ( $H_2$  at  $t_3$ )

These primary hazards occur sequentially along the timeline ( $t_0-t_3$ ) and therefore constitute a **compound consecutive event**. The two flooding processes are linked through the event-tree structure, indicating that **interactions between pluvial and coastal flooding processes** should be modelled, including potential amplification effects. At later time steps ( $t_4$ ), the combined flooding impacts lead to a **cascading effect** ( $CE_1$ ) associated with **electricity service disruption** ( $SD$ ). This disruption follows the flood impacts and represents a **secondary cascading hazard**, propagating the consequences of the initial hydrometeorological events into the urban system through interdependent critical infrastructure networks.

8. Considering the event-tree scenario, at which spatial scale(s) does the ICARIA modelling framework primarily operate?

(Select all that apply)

- Local
- Regional
- National
- Continental
- Global

9. Considering the event-tree scenario, at which temporal scale(s) does the ICARIA modelling framework primarily operate?

(Select all that apply)

- Seconds
- Minutes
- Hours
- Days
- Months
- Years
- Multi-temporal (different components operating at different temporal scales)

**10. Which factors and/or limitations would most influence the successful replication of the ICARIA modelling framework to different contexts?**

*(Select all that apply and provide a brief explanation in this regard)*

- Availability and quality of hazard, exposure/vulnerability parameters required by the modelling chain
- Computational requirements of the full workflow
- Other (specify): \_\_\_\_\_

Explanation: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

**SECTION 3 – Model setup, Data requirements and Outputs**

**11. What is the estimated effort required to prepare the input data so that they can be “ICARIA-ready”?**

*(Including harmonisation, preprocessing, format conversion, and quality checks)*

- Low (minor adjustments)
- Medium (moderate adjustments)
- High (substantial preparation work required, including gap-filling)
- Not estimable based on current information

Explanation: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

**12. To what extent does the performance of the ICARIA modelling framework depend on the high-quality or resolution of the input data?**

*(Select a value from 0 to 5, where 0 = ‘not dependent’ and 5 = ‘highly dependent’, and provide a brief explanation in this regard)*

- 0  1  2  3  4  5

Explanation: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

**13. What are the main data-related barriers for ICARIA modelling framework replication in different contexts?**

*(Select all that apply)*

- Restricted or proprietary access
- Limited spatial resolution
- Limited temporal resolution
- Outdated or inconsistent datasets
- Incompatible data formats
- Lack of documentation or metadata
- Fragmented or heterogeneous data sources
- Missing mandatory variables
- Other (specify): \_\_\_\_\_

**14. Considering the event-tree scenario, list all output datasets generated by the application of the ICARIA modelling framework:**

*(For each dataset, indicate the type of data, variables included, required spatial and temporal resolution, and preprocessing needs. We suggest using the example row as guidance!)*

OUTPUT DATA TYPE	VARIABLES INCLUDED	SPATIAL RESOL.	TEMPORAL RESOL.	POSTPROCESSING REQUIRED
<i>Example: Hazard maps</i>	Maximum water depth, flow velocity	500m	hourly data	Smoothing, clipping, and reprojection

**15. Considering the event-tree scenario, list all relevant adaptation measures that can be modelled and evaluated in their effectiveness through an “alternate run” of the modelling workflow:**

*(For each adaptation measure available for simulation, indicate the target hazard(s) and/or cascading effects; additional notes may be provided where relevant)*

ADAPTATION MEASURE	TARGET HAZARD(s) and/or CASCADING EFFECTS	NOTES
<i>Example: Urban green infrastructure</i>	Heatwave; pluvial flooding	...

**SECTION 4 – DSS integration**

**16. Does the DSS support the full modelling workflow for the event-tree scenario in the replication phase?**

*(Select the option that applies, and provide a brief explanation specifying which workflow components are not supported and why)*

- Fully supported
- Partially supported
- Not supported

Explanation: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

**17. Which components of the ICARIA modelling workflow are supported by the DSS during the replication phase?**  
*(Select all that apply)*

- Single-hazard assessment**  
Please, specify one or more hazard type(s) included: \_\_\_\_\_
- Multi-hazard assessment – compound coincident**  
Please, specify hazard types included: \_\_\_\_\_
- Multi-hazard assessment – compound consecutive**  
Please, specify hazard types included: \_\_\_\_\_
- Exposure / Vulnerability (including Dynamic Vulnerability) assessment**  
Please, specify the category of elements at risk included: \_\_\_\_\_
- Impact / Risk assessment**  
Please, specify damage types included: \_\_\_\_\_
- Cascading effect assessment**  
Please, specify cascading effect(s) included: \_\_\_\_\_
- Resilience assessment**  
Please, specify if through RAF, RAT or both: \_\_\_\_\_
- Adaptation measures identification**  
Please, specify key measure(s) from the Portfolio: \_\_\_\_\_
- Adaptation measures assessment**  
Please, specify measure(s): \_\_\_\_\_
- None of the above:** \_\_\_\_\_

**SECTION 5 – Replication effort & Resource requirements**

**18. What are the main cost drivers for the ICARIA modelling framework replication?**  
*(Select all that apply)*

- Licensing fees or proprietary software components
- Input data acquisition, harmonisation, and processing
- Integration and interoperability between framework components
- Personnel time for framework configuration and modelling
- Calibration and validation across multiple hazards, exposure/vulnerabilities, risk/impact, and resilience pathways
- Development of the adaptation and resilience modules
- Computational resources
- Other (specify): \_\_\_\_\_

5

**19. How would you estimate the overall cost required to replicate the full ICARIA modelling framework in a different context?**  
*(Choose the category that best reflects typical effort, and, if possible, provide an approximate cost estimate)*

< 10.000 €  
 10.000-20.000 €  
 20.000-50.000 €  
 > 50.000 €

Approximate cost estimate (optional): \_\_\_\_\_

**20. How long would it typically take to replicate the full ICARIA modelling framework in a different context?**  
*(Select one that applies)*

< 1 month  
 1–3 months  
 3–6 months  
 > 6 months

**21. Which implementation steps are usually the most time-consuming?**  
*(Select all that apply)*

Data collection and preparation  
 Data harmonisation and preprocessing across multiple datasets and scales  
 Parameterisation of the framework components  
 Calibration using local conditions across hazards, exposure/vulnerabilities, risk/impacts, and resilience  
 Integration and interoperability between ICARIA modelling framework components  
 Generation and post-processing of outputs  
 Other (specify): \_\_\_\_\_

**22. In your view, what are the main obstacles that could delay or increase the cost of replication of the ICARIA framework in a different context?**

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

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**Figure A1.** Example of the questionnaire administered to experts, illustrated here for the AMB CS. The same questionnaire was consistently used across the SLZ and SAR CSs.

## Annex B: Questionnaires for stakeholders

The **questionnaire administered to stakeholders** within the **AMB CS** is available at the following link: [https://docs.google.com/forms/d/e/1FAIpQLSdRxRWCxJUoI39KUM57doDLU6y7U-zBP46UoDMg64Y\\_TdiTMA/viewform](https://docs.google.com/forms/d/e/1FAIpQLSdRxRWCxJUoI39KUM57doDLU6y7U-zBP46UoDMg64Y_TdiTMA/viewform)

The **questionnaire administered to stakeholders** within the **SLZ CS** is available at the following link: <https://docs.google.com/forms/d/e/1FAIpQLSelG8FvOclx4TndQ-XYceDhrqPV6PD4iUisZnNzdVKKQ0822NQ/viewform>

The **questionnaire administered to stakeholders** within the **SAR CS** is available at the following link: <https://docs.google.com/forms/d/e/1FAIpQLSdKZPTAm7ld55mToCD4aWxBUcfPt0oN1RdYGXWRj7LMu930DA/viewform>

## Annex C: Data Management Statement

**Table C.1.** Data used in preparation of ICARIA Deliverable 4.3

Dataset name	Format	Size	Owner and re-use conditions	Potential Utility within and outside ICARIA	Unique ID
Climate projections (statistical downscaling)	txt and TIFF	>10GB	Open data	Climate risk assessment	10.5281/zenodo.10964398
Climate projections (dynamic downscaling)	txt and TIFF	>10GB	Open data	Climate risk assessment	10.5281/zenodo.14937418

**Table C.2.** Data produced in preparation of ICARIA Deliverable 4.3

Dataset name	Format	Size	Owner and re-use conditions	Potential Utility within and outside ICARIA	Unique ID
SLZ CS risk assessment results	SHP and TIFF	>10GB	Open data	Asset-level risk assessment	10.5281/zenodo.19129658
SAR CS risk assessment results	SHP and TIFF	>10GB	Open data	Asset-level risk assessment	na

<b>AMB CS risk assessment results</b>	SHP and TIFF	>10GB	Not public	Asset-level risk assessment	na
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DRAFT

More info: [www.icaria-project.eu](http://www.icaria-project.eu)

