ICARIA
Improving climate resilience of critical assets

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D4.2
Trial assessment

This project has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No. 101093806. The publication reflects only the authors' views and the European Union is not liable for any use that may be made of the information contained therein.

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Summary

Deliverable 4.2 presents the integrated implementation and validation of the ICARIA risk assessment framework and Decision Support System (DSS) across three case studies: the Barcelona Metropolitan Area (AMB), the Salzburg Region (SBG), and the South Aegean Region (SAR). The deliverable achieved two objectives: validating ICARIA's resilience and risk assessment tools through structured stakeholder trials and applying single- and multi-hazard risk assessments under present and future climate scenarios. Methodologies developed across project work packages were operationally integrated into a coherent analytical and decision-support environment. Hazard modelling outputs, climate projections, vulnerability assessments, and resilience tools were embedded directly into the DSS, ensuring scientifically robust, case-specific validation. Stakeholder trials confirmed the DSS's functionality and practical relevance, particularly its capacity to compare Business-as-Usual and adaptation scenarios, visualize spatial risk, and support planning decisions. Across the case studies, multi-hazard and cascading effects consistently amplified risks, though patterns varied by region and hazard type. Climate change acted as a risk multiplier, especially for compound events. Adaptation measures—ranging from green infrastructure and spatial planning to building reinforcement and ecosystem-based strategies—demonstrated measurable reductions in direct and indirect impacts.

Deliverable number	**Work package**	
D4.2	WP4	
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Internal reviewer(s)	**External reviewer(s)**	
Denis Havlik (AIT)	Beniamino Russo (UPC)	
Planned delivery date	**Actual delivery date**	
28/11/2025	24/02/2026	
Dissemination level	☐ **PU = Public** ☐ PP = Restricted to other program participants ☐ RE = Restricted to a group specified by the consortium. ☐ CO = Confidential, only for members of the consortium	

Document history

Date	Version	Author	Comments
26/08/2025	1.1	Alex de la Cruz (AQUA)	Initial draft
12/02/2026	1.2	Alex de la Cruz (AQUA)	First full draft
10/02/2026	1.3	Sofía Pacho (AQUA)	Second full draft
17/02/2026	2.0	Beniamino Russo (UPC) Denis Havlik (AIT)	Revised draft
24/02/2026	3.0	Alex de la Cruz (AQUA)	Final document

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List of Acronyms and Abbreviation

Acronyms table	
AIT	Austrian Institute of Technology
AMB	Barcelona Metropolitan Area
CC	Climate Change
CCF	Climate Change Factor
CLC	Corine Land Cover
CO	Confidential (Dissemination level)
CoP	Community of Practice
CS	Case Study
DoA	Description of Action
DSS	Decision Support System
DTM	Digital Terrain Model
EESL	Event Extreme Sea Level
EFFIS	European Forest Fire Information System
ESL	Extreme Sea Level
FWI	Fire Weather Index
HS	Heat Stress
IREC	Catalonia Institute for Energy Research
PP	Restricted to other program participants
PU	Public (Dissemination level)
RAF	Resilience Assessment Framework
RAT	Resilience Assessment Tool
RCM	Regional Climate Model
RQ	Research Question
SAR	South Aegean Region
SLZ	Salzburg Region
SLR	Sea Level Rise
SSN	Synthetic Sewer Network
SSO	Strategic Subojective
SSP	Shared Socioeconomic Pathways
TGM	Trial Guidance Methodology
UPC	Technical University of Catalonia
WP	Work Package
WWPT	Wastewater Treatment Plant

Executive summary

Deliverable 4.2 documents the integrated implementation and validation of the ICARIA risk assessment framework and Decision Support System (DSS) across three ICARIA case studies: the Barcelona Metropolitan Area (AMB), the Salzburg Region (SBG), and the South Aegean Region (SAR). The activities reported fulfil the dual objective of the deliverable: testing and validating the ICARIA resilience assessment tools and DSS through structured trial activities with stakeholders and developing and applying single- and multi-hazard risk assessments for critical assets under present and future climate scenarios. The results provide clear evidence of methodological integration, scientific robustness, and practical applicability.

A central outcome of Deliverable 4.2 is the operational integration of methodologies and tools developed under WP1, WP2 and WP3. Risk assessment methods, climate change projections, single- and multi-hazard models, impact quantification approaches, resilience assessment tools and DSS functionalities were combined into a coherent analytical and decision-support framework. The outputs of the hazard and risk modelling activities were directly embedded into the DSS and used as core input data during the trial phase. This ensured that the validation process was grounded in scientifically robust and case-specific information rather than hypothetical datasets. The interdependency between risk modelling and decision-support functionality constitutes a key strength of the ICARIA approach, demonstrating that the DSS operates as an integrated analytical environment capable of supporting structured climate risk evaluation and adaptation planning.

The trial activities carried out in AMB, SBG and SAR confirmed the technical functionality and decision-support potential of the ICARIA DSS. Through the adapted Trial Guidance Methodology, stakeholders were able to test the main DSS features, including scenario creation, upload and validation of hazard, exposure and vulnerability datasets, execution of risk and resilience assessments, comparison between Business-as-Usual and adaptation scenarios, and visualization and export of results. Across the three case studies, participants recognized the added value of integrating climate projections, multi-hazard risk modelling, resilience assessment and adaptation evaluation within a single platform. The capacity to compare scenarios and to visualize spatially explicit risk outputs was consistently highlighted as particularly useful for supporting technical analysis and facilitating dialogue between experts and decision-makers.

Stakeholder feedback indicated moderate to high satisfaction levels and confirmed the relevance of the tool for practical planning contexts. At the same time, the trials identified areas requiring further refinement, such as enhanced transparency of modelling assumptions, clearer guidance in the resilience assessment modules, improved visualization interfaces and simplification of data preparation processes. These findings are consistent with the prototype stage of development and provide a clear roadmap for future enhancement before the end of ICARIA. Importantly, none of the identified limitations undermined the perceived usefulness of the system; rather, they reflect the natural evolution from research prototype toward operational tool. The successful completion of the trial activities therefore demonstrates the fulfilment of the first objective of the deliverable.

The risk assessment component of Deliverable 4.2 illustrates the flexibility and applicability of the ICARIA framework across diverse climatic and geographic contexts. In AMB, extreme precipitation and

coastal flooding driven by sea level rise and storm surge were analyzed using multiple return periods and climate change scenarios. The modelling framework incorporated a detailed representation of the metropolitan drainage system, allowing assessment of pluvial flooding under both current and future climatic conditions. The multi-hazard analysis combining pluvial events with elevated sea levels revealed amplification effects associated with reduced drainage capacity and backflow mechanisms in low-lying urban areas. Adaptation measures including porous pavements, green roofs and bioretention areas demonstrated measurable reductions in runoff generation and peak flows, particularly in densely urbanized zones.

Overall, the comparison between single-hazard and multi-hazard scenarios confirms that compound flooding systematically amplifies risk across all receptors in the metropolitan area of Barcelona, with the most critical increases concentrated in low-lying coastal municipalities. For pedestrians, the extent of high-risk areas grows by approximately 4–8% under multi-hazard conditions at the metropolitan scale, but local increases in coastal neighborhoods frequently exceed 10%, revealing strong spatial concentration of impacts. A similar pattern is observed for transport, where high-risk road length increases by up to 5% globally and by 10–13% in specific coastal municipalities such as Barcelona, Badalona, and Castelldefels. For properties, multi-hazard interactions lead to economic damage increases of around 4–7% for T10–T100 events and up to 10–15% in extreme cases, with Expected Annual Damage rising by roughly 5% compared to single-hazard conditions. These increments, although moderate at the regional scale, become very intense in localized coastal hotspots due to sewer backflow and reduced drainage capacity caused by elevated sea levels. Moreover, cascading effects—particularly in the electricity sector—demonstrate how compound flooding can propagate beyond directly flooded areas, increasing repair times by 15–20%, expanding the number of affected consumers by more than 40% in extreme scenarios, and amplifying indirect economic losses across interconnected sectors. Climate change acts as a consistent risk multiplier, worsening the magnitude and frequency of extreme events and progressively shifting even frequent, historically negligible events into economically relevant risk drivers.

In contrast, the adaptation scenario demonstrates a consistent and measurable reduction of risk across all receptors, partially offsetting the intensification driven by climate change. For pedestrians and transport, high-risk areas are reduced by approximately 10–12% for T10 events and between 7–10% for more severe return periods, while reductions for frequent events (T1) can reach 17–19%. For properties, economic damages decrease by 14–18% for T10 events and by 7–10% for extreme storms, with indirect economic risk reduced by roughly 11–15% across projection horizons compared to the multi-hazard baseline. Although adaptation does not eliminate the upward trend in damages toward the end of the century, it moderates both direct and cascading impacts, limiting the propagation of disruptions through critical infrastructures and the metropolitan economy. These results highlight that, in a context of accelerating climate change and increasing compound hazard interactions, proactive and system-wide adaptation strategies are essential to contain the intensification of coastal risks, reduce cascading failures, and enhance the long-term resilience of the AMB.

In the Salzburg Region, fluvial flooding and windstorms were assessed under present and projected climate conditions. Hydrodynamic modelling of riverine flooding in the Alpine valley context enabled spatially explicit evaluation of exposure and economic damage across buildings and infrastructure. Wind hazard analysis focused particularly on electricity infrastructure, allowing assessment of structural vulnerability and potential service disruptions. Adaptation scenarios such as relocation of flood-exposed buildings, implementation of early warning systems and structural reinforcement against wind loads illustrated the complementary roles of structural and non-structural measures in reducing both direct and indirect impacts.

Overall, the Salzburg case study shows a differentiated risk pattern compared to coastal metropolitan regions, with fluvial flooding and extreme windstorms representing the dominant hazards. Under single-hazard conditions, direct flood damages to residential properties range from about €30,000 for 2-year events to approximately €9 million for 100-year events, while severe windstorms can generate losses of around €6–7 million in the most exposed western areas of Mittersill. Climate change projections do not substantially alter fluvial flood depths in the main Salzach river due to existing river engineering measures, but they maintain or slightly intensify the magnitude of extreme events, meaning that high-return-period floods and rare windstorms remain the principal drivers of risk. In the multi-hazard configuration (wind-induced debris affecting river roughness), impacts remain largely similar to the single-hazard case, with only localized increases in flood depth of up to 0.5 m along smaller tributaries and negligible changes in aggregated property damages. Consequently, total direct economic losses between single- and multi-hazard simulations differ only marginally (generally below 5%). However, cascading effects—particularly those related to electricity supply disruptions during extreme wind events—highlight systemic vulnerability. In the 2038 stress-test event, more than 70% of buildings fall into high cascading risk classes and associated indirect economic impacts (via Energy Not Supplied and Additional Generation Costs) concentrate heavily in these zones. While gradual climate change under SSP1-2.6 shows limited cascading amplification, rare extreme events continue to pose disproportionate indirect losses, demonstrating that systemic risk in Salzburg is driven more by extremes than by gradual hazard intensification.

The adaptation scenarios clearly demonstrate substantial potential for risk reduction across all receptors. Relocation of flood-prone industrial assets reduces direct flood damages by approximately €2 million for events with return periods of 30 years and above, corresponding to reductions on the order of 20–25% for those scenarios. Early warning systems for traffic significantly lower vulnerability levels, reducing flood-related traffic disruption from predominantly high-risk classes to mostly low or medium risk conditions. The most pronounced effect is observed for windstorm adaptation: strengthening building standards decreases direct wind damage from approximately €6–7 million to €0.3–0.6 million, representing a 90–95% reduction under modeled wind speeds and still 70–80% reduction under amplified gust sensitivity scenarios. These results underline that, although multi-hazard interactions in Salzburg do not dramatically amplify direct flood damages, cascading electricity impacts and extreme wind events remain critical risk drivers. Climate change will continue to exacerbate the consequences of rare high-impact events, even where mean conditions remain relatively stable. Proactive adaptation—through spatial planning, stricter building codes, and improved preparedness—proves highly effective in reducing both direct and indirect losses and in strengthening the resilience of the regional socio-economic system against future extreme events.

In the South Aegean Region, wildfire risk in Rhodes and heatwave impacts in Syros were analyzed using climate projections under different emission pathways and time horizons. Wildfire hazard assessment based on fire weather indicators highlighted the sensitivity of Mediterranean island environments to climatic drivers. Heatwave modelling quantified thermal stress on buildings through the integration of downscaled temperature projections and satellite-derived land surface data. Adaptation strategies including reforestation with less flammable species, fuel management, and building retrofit measures such as insulation, cool roofs and passive cooling techniques demonstrated the potential to reduce both hazard intensity and vulnerability.

Overall, the South Aegean results highlight a clear intensification of risk under multi-hazard and climate change scenarios, particularly for economic assets and ecological receptors on Rhodes, while heat stress remains a dominant driver for buildings in Syros. In Rhodes, the transition from single-hazard wildfire to multi-hazard conditions (wildfire combined with extreme wind and heat) produces a moderate but spatially relevant increase in high-risk areas, generally on the order of 5–10% in central and eastern parts of the island, where critical infrastructure, agricultural assets, and past wildfire scars overlap. Ecological risk shows a more pronounced escalation, with a clear shift toward higher categories under both SSP126 and SSP585, and high-risk (categories 4–5) zones expanding by roughly 10–15% compared to historical conditions. For economic assets, multi-hazard scenarios slightly amplify the extent of category 4–5 risk areas (around 5–8%), confirming that compound extremes increase the likelihood of severe wildfire-related losses to power networks, roads, and agricultural production. Although direct impacts on people remain comparatively low in spatial extent, the 2023 wildfire event—forcing the evacuation of approximately 19,000 people—demonstrates the potential for cascading social disruption even in areas mapped as moderate physical risk. Power outages, water supply interruptions, and agricultural losses illustrate how cascading effects can rapidly propagate through interconnected systems, amplifying indirect economic damages well beyond the burned area. In Syros, heatwave risk already affects more than 60% of buildings in high-risk categories under historical conditions, and while near-term climate scenarios show limited redistribution between classes, climate change maintains and gradually intensifies extreme heat conditions, ensuring that exposure remains structurally high. Overall, climate change acts as a persistent risk multiplier, particularly for ecological systems and wildfire-prone landscapes, reinforcing the severity and frequency of extreme compound events across the region.

In contrast, the adaptation scenarios demonstrate substantial and consistent risk reduction across all major receptors. On Rhodes, vegetation replacement with less flammable species reduces category 5 ecological risk areas by approximately 30–32% in both single- and multi-hazard simulations, with category 4 areas decreasing by around 10%, indicating a marked lowering of extreme wildfire susceptibility even under future climate conditions. For economic assets, high-risk (category 4–5) areas decline by roughly 20% under single-hazard adaptation and by 28–34% under multi-hazard adaptation scenarios, confirming that ecosystem-based measures can significantly reduce both direct and compound-event risk. In Syros, building retrofitting shifts a large share of properties from high-risk classes (4–5) to moderate classes (2–3), effectively reducing the proportion of highly vulnerable buildings by an estimated 25–35% across historical and future heatwave scenarios. Importantly, adaptation not only lowers direct damages but also limits cascading impacts—reducing the probability of prolonged power outages, service interruptions, and mass evacuations during extreme events. While adaptation does not eliminate risk entirely, especially under high-emission pathways, it substantially moderates the upward trend in damages and enhances systemic resilience. The results for the South Aegean therefore underscore that, in a region highly exposed to wildfire–heat–wind interactions, proactive, ecosystem-based and structural adaptation strategies are essential to counterbalance the escalating pressures imposed by climate change and compound extreme events.

Across all case studies, the incorporation of multiple return periods and SSP-based climate scenarios enabled assessment of short-, mid- and long-term risk evolution. The results confirm that climate risk amplification is hazard-specific and spatially differentiated, underscoring the importance of locally tailored modelling approaches. The analyses also demonstrate that adaptation effectiveness is context-dependent, varying according to hazard type, spatial configuration and sectoral exposure.

An important contribution of Deliverable 4.2 lies in the explicit consideration of multi-hazard interactions and cascading effects. The compound pluvial–coastal scenario in AMB illustrated how combined drivers can increase flood impacts beyond those estimated under single-hazard assumptions. In SBG and SAR, the evaluation of infrastructure and service disruptions highlighted the relevance of system-level vulnerabilities and indirect effects. These findings indicate that moving from single-hazard to multi-hazard frameworks can alter risk prioritization and adaptation planning decisions, particularly in interconnected urban and infrastructure systems.

The integration of quantitative risk modelling with resilience assessment and adaptation scenario testing within the DSS represents a significant advancement over conventional risk studies. The ability to compare Business-as-Usual and adaptation scenarios within a harmonized framework allows evidence-based evaluation of risk reduction capacity. This strengthens transparency in decision-making and supports structured engagement between scientists, infrastructure operators and policymakers.

1 Introduction to Project ICARIA

The number of climate-related disasters has been progressively increasing in the last two decades and this trend could be drastically exacerbated in the medium- and long-term horizons according to climate change projections. It is estimated that, between 2000 and 2019, 7,348 natural hazard-related disasters have occurred worldwide, causing 2.97 trillion US$ losses and affecting 4 billion people (UNDRR, 2020). These numbers represent a sharp increase of 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 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 modeling 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 a sense that its local effects can result in significant increases in cost of potential losses for unplanned outages and failures, as well as maintenance – unless an effort is undertaken in making 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. 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, SO5); 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).

- 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 studies regions

- SSO3.- Quantify uncertainty and manage data gaps through model input requirements and innovative methods
- SSO4.- Increase the knowledge on climate related disasters (including interactions between compound events and cascading effects) by developing and implementing advanced modeling for multi-hazard assessment
- SSO5.- Better assessment of holistic resilience and climate-related impacts for current and future scenarios
- SSO6.- Better decision taking for cost-efficient adaptation solutions by developing a Decision Support System (DSS) to compare adaptation solutions
- SSO7.- Ensure the use and impact of the ICARIA outputs

2 Objectives of the deliverable

Deliverable 4.2 reports the outcomes of Task 4.2. As defined in the DoA, this task integrates the outputs of WP1 (risk assessment methodology and climate change projections), WP2 (single and multi-hazard assessment) and WP3 (impact quantification, resilience assessment and Decision Support System (DSS) tools development) in the context of the project Case Studies (CS). Specifically, Task 4.2 involves two parallel and codependent activities:

1. The first one is the testing of the ICARIA resilience assessment tools and DSS following the Trial Guidance Methodology (TGM) as presented in Deliverable 4.1 (Havlik et al., 2024).
2. The second one is the development of extreme event risk assessment for critical assets according to the CS trial architectures defined in Deliverable 1.1 (Turchi et al., 2023) and updated in this document. Importantly, the outcomes of the second activity, including risk maps and indicators, are an essential part of the tool testing in activity number one, as they are the basic data input for the tool's functioning and demonstration.

Considering the above, the objectives of Deliverable 4.2 are as follows:

1. Report on the trial activities developed to evaluate the ICARIA tools, done in the context of the ICARIA CS involving multiple stakeholders and end users.

2. Present the results of single and multi-hazard risk assessment for critical assets. This involves direct and indirect impact assessment of historic events and future climate change scenarios, the evaluation of cascading effects and testing the risk/impact reduction capacity of adaptation measures.

Considering the duality of content and objectives in Deliverable 4.2, its contents are organized as follows: Chapters 1 and 2 present a generic introduction to the project ICARIA (to contextualize readers) and define the document's objectives, respectively.

Chapter 3 is focused on the trial activities developed to test the ICARIA tools with relevant stakeholders, covering the contents of objective 1. Firstly, it presents relevant organizational and methodological changes adopted with respect to the original planning in Deliverable 4.1. Secondly, it details the organization of the trial event in each CS. Thirdly, it shows the event outcomes and stakeholders' feedback. Finally, it summarizes lessons learned.

Activities related to hazard risk assessment (objective 2) are reported from chapter 4 to 7. Chapter 4 presents the ICARIA risk assessment framework, and all the single and multi-hazard assessment models developed for the trial activities in each CS. Furthermore, it specifies the climate change scenarios and extreme events considered in each case. Chapters 5, 6 and 7 present the corresponding risk assessment results for the AMB, SBG and SAR case studies, respectively including single and multi-hazard drivers, cascading effects and testing of adaptation measures.

Lastly, Chapter 8 provides the overall conclusions and lessons learned from the reported activities.

Importantly, Deliverable 4.2 and its contents are proof of fulfillment of Milestone 3.

3 The ICARIA Trials

This section starts with an overview of the way Trial Guidance Methodology (TGM) was used in ICARIA, including the “interpretation” of the methodology we decided to implement in order to align it with the reality of the Climate Adaptation domain and the case study regions and finishes with a presentation of the three regional trials and a summary of the data gathered from trial participants.

3.1 Trial Guidance methodology in ICARIA

The ICARIA testing and validation process is an extension of the Trial Guidance Methodology (Fonio et al., 2023) (Fonio et al., 2023), which has been initially developed and successfully tested by the DRIVER+ project1 - DRiving InnoVation in crisis management for European Resilience, 2014-2020 (FR7 program, Grant agreement ID: 607798, 2014-2020;).

Trial Guidance Methodology (TGM) is a structured methodology for assessing the innovation potential of socio-technological solutions for specific stakeholders or stakeholder organizations. TGM provides a **structured approach for assessing the innovative potential of novel solutions to address specific societal or organizational needs (gaps)**. The TGM handbook (Fonio et al., 2023) provides step-by-step guidelines for designing the trials, a list of roles and responsibilities, tools, and methods to perform a trial through a clear, pragmatic and systematic approach, evaluate the outcomes and identify lessons learned. TGM rules and methods are strict enough to ensure appropriate replicability of the results while being flexible enough to ensure wide applicability of the methodology.

Thanks to its generic nature, TGM has already been successfully applied in multiple H2020 and HE projects (Fonio et al., 2023) and entered a standardization process through the publication of the CEN Workshop Agreement CWA 17514 (CEN-CENELEC Management Centre, 20202). Despite being designed for use in a crisis management context, its successful application in the RESILOC3 - Resilient Europe and Societies by Innovating Local Communities project indicates that TGM is applicable in a wider context of societal resilience, with minor adaptations. Most importantly from the ICARIA perspective, **TGM helps to objectively assess the project results, by insisting on an up-front definition of the gaps, objectives and research questions the trial will address as well as on the up-front definition of data that will be collected during the trial and the ways this data will be interpreted in trial assessment**.

Moreover, TGM foresees **active involvement of key stakeholders in trial preparation, execution and assessment of the trial results**. In ICARIA, this link between the core trial team and relevant stakeholders is established through **Communities of Practice (CoPs)** and, more specifically, through CoP events that are defined in Section 4 of the project deliverable D5.4 “Stakeholder Engagement Plan” (Truchi et al., 2023). In the context of TGM, following definitions apply.

TGM describes the three main phases of the trial i.e., (**planning, execution, and evaluation**), and provides detailed description of the activities, methods, support tools and practical examples for designing, executing and evaluating the trials. Each of the phases is further split into separate steps, as shown in **Table 1**. In the context of ICARIA, this deliverable corresponds to the Evaluation phase of the TGM. It summarizes the results and lessons learnt during the trial execution.

Table 1. DRIVER + Trial guidance methodology - all steps

DRIVER+ Trial Guidance Methodology		
Step Zero	Gaps	Identification of current problems and needs the stakeholders are facing.
	Trial context	Comprehensive description of the gap-specific aspects and factors.
Preparation	Trial Objective	Defining the specific goals and desired achievements. (SMART)
	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 in order to answer the research question, including the methods required on 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 in the tester's operations.
	Dry Run 1	First test run of the trial.
	Dry Run 2	Second test run (full test).
	Trial Run	Execution of the planned trial.
Evaluation	Data Quality Check	Identification of possible deviations of the data
	Data analysis	Analyzation 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.

3.2 Re-interpreting the TGM methodology for use in ICARIA

3.2.1 Rewording the relevant naming conventions

TGM has been developed for use in the crisis management context but known to be useful also in the context of Climate Action. D4.1 "Trial design" (Havlik et al, 2024) already anchors the methodology in the Climate Action space, mainly by adapting the naming conventions to those ICARIA stakeholders are familiar with, shortening the duration of the final trial event and acknowledging that the solutions to be trialed are already decided upon by project design and still need to be developed rather than already existing and waiting to be chosen for use in the trial (or not).

In addition, the following key vocabulary definitions were repeated over and over again to ensure everyone working on the project and the CoP members share the same understanding thereof.

- **Trial** is an assessment of the performance, qualities, or suitability of solutions for current and emerging needs in such a way that relevant stakeholders can execute it following a pragmatic and systematic approach.
- **Solution** is a combination of one or more processes and/or tools with related procedures that can potentially contribute towards resolving the operational gaps of the relevant stakeholders.
- **"Capability gap" (Gap)** is a difference between a current capability and the capability necessary for an adequate performance of different tasks.
- **Mini trials** are specific to ICARIA and do not exist in TGM, but largely follow the same methodology. As the name indicates, mini-trials feature their own objectives, research questions, data collection plans, evaluation approaches and metrics. With the innovative potential of ICARIA solutions already assessed through trials, the mini trials will mainly be used to assess the transferability and socio-economic impact potential of the trialed solutions and scenarios to the areas where the availability of the data is not guaranteed as the same level as it is for the trials.
- **Demos** are a tool to advertise the project results to the wider public and assess their interest in the exploitation of the project results, mainly in the trial regions. They could be organized as a "second coming of the mini-trials for a wider public", or as a presentation of the key findings of ICARIA trials and mini-trials (e.g., we might decide to show a recording made at previous events and discuss it with demo participants).

3.2.2 Shortening the main trial event duration & adding preliminary events

Recommended duration of the final trial event in TGM is 1.5 to 2 full working days. This fits well with the schedule of exercises first responders are used to. Unfortunately, this is at odds with the reality of the stakeholders participating in ICARIA CoP and trials - especially for those that aren't paid to participate in the project. For them, a full day event is already difficult to participate at. A decision to shorten the trial event duration to one day was therefore already reported in chapter 5.5 "Trial Scenario formulation" of D4.1. In subsequent work, it was realized that the trial event organization shown in Table 13 of D4.1 is sub-optimal for two reasons:

1. One day event doesn't provide enough time for hands-on testing of the solutions, thus de-facto degrading the trial event into a glorified demonstration.
2. Even a one-day event turned out to be too long for ICARIA stakeholders and we had to shorten it to a half day event.

Once these two factors were accounted for, it became obvious that we have to completely re-thing the trialing process. The solution we came up with was to **effectively split the trial event into several events and to concentrate only on validation of the ICARIA DSS at the final trial event**. This allowed us to organize a hands-on DSS testing by the stakeholders despite short trial event duration, while the RAF and RAT were validated through multiple hands-on testing sessions with relevant stakeholders prior to the main trial event.

3.2.3 Limiting the number of trial participants

In addition, we also realized that there is **no sense in involving a massive amount of people in the trial**. Due to the nature of ICARIA solutions, we didn't need any "boot on ground" and the number of stakeholders that will ever actively use the tools is limited.

3.2.4 Combining the trials with mini trials and demonstrations

Which brings us to the next deviation from the TGM: combining the trials with "**mini trials**" and "**demonstrations**", as illustrated in (**Figure *1***).

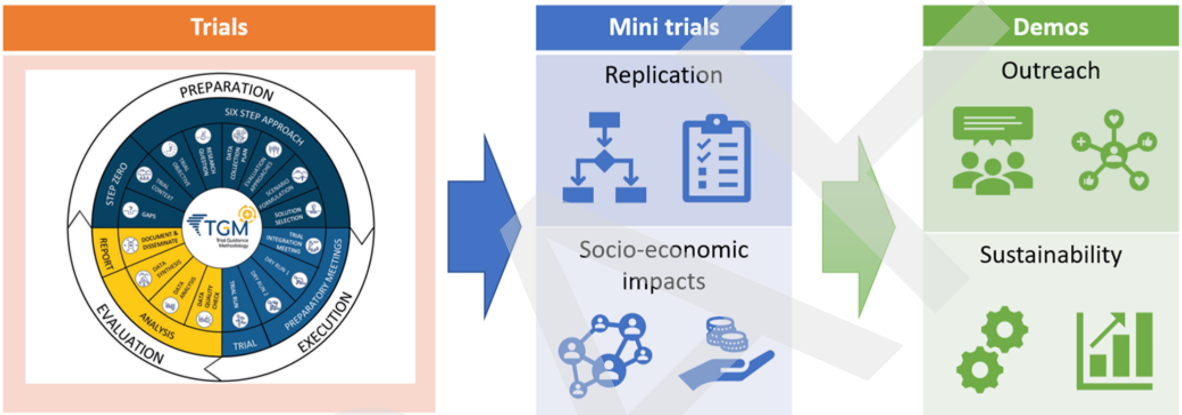


Figure 1. Overarching ICARIA methodology for assessing the solutions developed in the project (From D4.1)

As the word suggests, the mini trials are "lightweight" trials. Their design and organization follow the TGM methodology, but their organization is simpler to do due to following factors:

1. Mini trials need not be designed from scratch. Instead, we can start with an existing trial design and adopt / simplify it.
2. The aim of the mini trials is to assess the potential impacts of the ICARIA solutions. This has two main aspects: (1) assessing the replication potential of ICARIAs software and modelling methods, and (2) assessing the potential socio-economic impacts of ICARIA tools and recommendations. Consequently, hands-on validation of ICARIA software by event participants isn't necessary for a mini trial.

Full specifications of the mini trials will be disclosed in the upcoming D4.3 deliverable.

Finally, the demonstration is the usual "feel well" final project event, where ICARIA results will be presented in the best possible light and exploitation potential and sustainability therefore discussed with participants.

3.3 Trial organization

ICARIA Trial organization is already described in deliverable D4.1, but we have decided to summarize it here for readers convenience.

3.3.1 ICARIA trial objectives

Trial objectives indicate the overarching goals and aspirations of the trial team. They are intimately related to trial gaps and must be formulated in a SMART way. ICARIA trial objectives were defined in D4.1 and did not change afterwards.

Overarching objective (slogan) of ICARIA trials is to assess the capability of the ICARIA tools and models to improve the understanding of the climate resilience and climate change preparedness among local risk owners (authorities and critical asset operators) by simulating the impact of extreme multi-hazard events on critical infrastructure and helping the stakeholders to decide which adaptation options to implement.

Five specific trial objectives are also quite generic and shared across trials (Table 2).

Table 2. ICARIA Trial specific objectives (from D4.1)

Obj. No.	Objective
O1	Validate the **plausibility of ICARIA data and modelling results (hazards, impacts/damage estimates, impacts of adaptations)**.
O2	Validate the **appropriateness (relevance, effectiveness, side effects, societal justice) of the adaptation measures** suggestions provided by ICARIA solutions.
O3	Validate the **capability of proposed adaptation measures to reduce impacts**.
O4	Validate the capability of the ICARIA tools and models to **simulate impact associated with the long-term changes in weather patterns (caused by climate change) on critical infrastructure assets.**
O5	Assess to what extent/how ICARIA models/data/tools can help Regional Authorities and other stakeholders to **assess the CC vulnerability/resilience (strengths and weaknesses) of their critical infrastructure assets.**
O6	Assess to what extend/how ICARIA models/data/tools can help the Regional Authorities and other stakeholders to **assess and improve the CC adaptation plans for their critical infrastructure assets**

The objectives of the three case studies are centered on the analysis of relevant assets—rather than exclusively critical infrastructures—within three distinct contexts: an alpine region (the Austrian case study in Salzburg), a Mediterranean archipelago (the South Aegean Region in Greece), and one of the most densely populated metropolitan areas in Southern Europe (the Barcelona Metropolitan Area in Spain).

3.3.2 ICARIA research questions

Research questions connect different aspects of the trial: they address specific trial gaps, need to be answerable in an objective way within the trial, and need to be understood and approved by all trial stakeholders. Good research questions are formulated in a simple and easy-to-understand way and have a clear relation to trial gaps and objectives. ICARIA trial teams have decided to group the research questions for trials and mini trials into following RQ dimensions:

- **(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 trialed solutions?", "how do proposed adaptations contribute to just transition?")

The research questions defined in D4.1 (see **Table 3**) have proven to be useful in the project and didn't need to be changed during the trial execution phase.

Table 3. ICARIA research questions for the trials (from ICARIA D4.1)

RQ No.	Research Question	RQ dimension
RQ-Sci1	How plausible/reliable are ICARIA data/modelling results?	Sci
RQ-Sci2	How easy/difficult/expensive would it be to apply the ICARIA solutions in new regions?	Sci
RQ-Sci3	Which data/modelling aspects of ICARIA solutions need to be further developed/improved?	Sci
RQ-Sci4	To what extend does the functionality of the ICARIA tools go beyond the state of the art/ what is currently used in the region?	Sci
RQ-Ex1	How easy or difficult is it to use the solutions?	Ux
RQ-Ex2	How easy or difficult is it to understand the results/recommendations offered by the solutions?	Ux
RQ-Ex3	What needs to be done to improve the user experience / usability of the solutions?	Ux
RQ-Acc1	How useful is ICARIA methodology for the Regional Authorities and other stakeholders?	Acc
RQ-Acc2	How useful are ICARIA solutions for the Regional Authorities and other stakeholders?	Acc
RQ-Acc3	Do potential users want to use this type of solutions in their work?	Acc
RQ-Acc4	Which improvements / additional features would make the ICARIA methodology and/or solution(s) significantly more attractive for potential users?	Acc
RQ-Soc1	How much socioeconomic impact (including gender and ethics issues) do trial participants anticipate from ICARIA methodology and solutions?	Soc
RQ-Soc2	What kind of socioeconomic impacts (including gender and ethics issues) do trial participants anticipate from use of ICARIA methodology and solutions?	Soc

ICARIA research questions were defined in D4.1 and did not change afterwards.

Questions Ux1 to Ux3 (User experience) were accidentally named Ex1 to Ex3 (for “experience”) in D4.1. We have decided to keep this naming convention here, to insure consistency across ICARIA deliverables.

3.3.3 ICARIA data collection plan

ICARIA data collection plan, as defined in section 4.3 of the D4.1 document was only indicative and needed to be further refined during the trial execution phase. ICARIA Research questions cannot be resolved by a single data collection method. A combination of different methods was therefore used to collect relevant data and eventually resolve the research questions, as indicated in Figure 2.

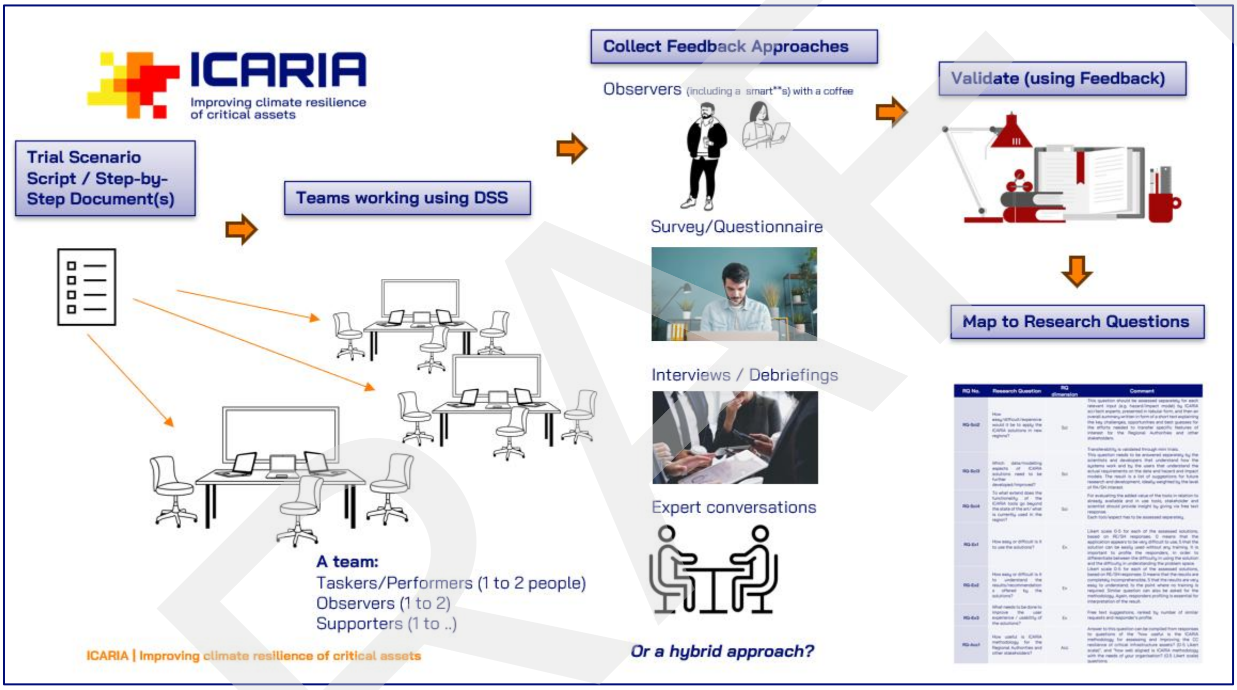


Figure 2. Overview of ICARIA trial organization, data collection and RQ assessments

In short, the trial teams were provided with following recommendations and related generic questionnaires developed in English language:

1. **Primarily resolve the questions related to Science and technology (Sci) by scientists and developers working in the project**, prior to trial event, with additional validation of Sci1, Sci3 and Sci4 questions by trial participants where possible. For this collection method, a generic framework for assessing the plausibility (Sci1), transferability (Sci2) and added value/uniqueness of ICARIA scientific methods (Sci3, Sci4) were developed by the project team.
2. **Primarily resolve questions related to user experience (UX) by observers**. For this data collection method, (1) a **detailed training/tutorial script** that is followed by (part of the) trial

participants and (2) **a structured questionnaire** that is aligned with this script, mapped to research questions and used by dedicated observers to report their observations during the trial event was designed and adapted to each of the trials.

3. **Primarily resolve the questions related to user acceptance and sustainability (Acc) through interaction with the stakeholders.** For this, following methods were recommended to trial owners: (1) fully fledged surveys; (2) interactive surveys (e.g., mentimeter) and/or participatory activities embedded the trial events; and (3) interviews with key stakeholders.

Furthermore, a recommendation was made to use the following types of surveys and the necessary generic survey templates/questions developed in the English language.

1. Short/interactive survey to profile the participants and assess their expectations before the trial event.
2. Observers' questionnaire that helps observers resolve the relevant questions, aligned with the trial scenario scripts (section 3.4.4.)
3. Another short/interactive questionnaire was designed to collect responses to Sci1, Sci4, Acc and Soc questions.

Fully fledged surveys were developed using google forms and the short/interactive ones using the Mentimeter. To avoid privacy issues, the surveys did not ask for the personal data (name, e-mail, etc.) from trial participants. All the data collection methods were later translated to the regional languages (Spanish, German, Greek) and, where necessary, adopted for specific trials.

Finally, a decision was made to leave the task of resolving questions related to socioeconomic impacts to the mini trials.

3.3.4 ICARIA trial scenarios

ICARIA trial scenario, as defined in section 4.4 of the D4.1 document was meant to be a starting point for designing more detailed scenarios but turned out to be inadequate for the reasons mentioned in section 2 of this document. Trials had to be shortened, RAF and RAT were tested by stakeholders prior to the main trial event and the actual trial concentrated on validating the Decision Support Tool through a hands-on approach. New generic trial event script is shown in **Table *4***:

Table 4. Generic trial organization script (new)

No	Task	Time	Recommendation
0	Arrival of participants	~15 min	
1	Welcome and introduction of the meeting	~ 15 min	Initial mini-surveys (profiling)
2	Presentation of the study	~ 30 min	Ask users to validate the plausibility of presented scientific results (RQ-Sci1)
3	Preparation for the participatory evaluation of the Decision Support System	~15 min	Explain how the participatory evaluation works, assign roles to testers & observers.
4	Participatory evaluation	~2h + ~30 min break	Hands on evaluation of the tools Validation (mainly) of Ux research questions by observers
5	Conclusions and closing of the meeting	~30 min	Final survey or discussion. - concentrate on Sci3, Sci4, Acc and Soc questions.

Detailed test scenarios for validating the different features of ICARIA solutions have then been defined and later adopted specific needs of each of the trials. These scripts concentrate on hands on testing of the ICARIA Decision Support System and cover the following key features:

Access and Setup: Participants are instructed to access the tool at https://icaria.draxis.gr using the provided credentials. They create projects and scenarios within the Project Manager, specifically creating one scenario to work with throughout the trial.

Risk/Impact Assessment Testing: Participants are instructed to test the Risk/Impact Assessment functionality by uploading four types of data: hazard maps, exposure maps, area maps and vulnerability curves. The system then processes these inputs, and participants are instructed to monitor the calculation progress through the Risk/Impact Status button.

Resilience Assessment Testing: While impact calculations are processing, participants are instructed to explore the two resilience assessment tools: RAF (Resilience Assessment Framework) and RAT (Resilience Assessment Tool). To save time, participants can be instructed to access a shared project with pre-completed assessments rather than designing a new one from scratch. They should view RAF/RAT charts, download PDF reports, and explore editing and cloning functions.

Adaptation Measures Testing: Participants are instructed to explore the adaptation measures inventory through the ICARIA Measures database. They test the search and filter functionalities, view measure characteristics, and learn how to assign measures to projects and scenarios. They are also instructed to explore tools for prioritizing, comparing, and creating custom adaptation measures.

'Business as Usual' (BAU) and 'Adaptation' scenarios can be either created by participants for comparison, or pre-created scenarios used for efficiency.

Map Visualization and Results Testing: Participants are instructed to extensively test the Map Viewer functionality by adding layers from 'My layers' (their own calculated economic impact layers) and 'Shared Layers' (pre-calculated business as usual and adaptation scenario layers). They should navigate the map using click-and-drag, zoom controls, and click on points to view attribute tables showing economic impact results grouped by zones. They can also add climate projection layers for relevant hazards.

Comparison and Analysis Tools Testing: Participants are instructed to test the Split View functionality to compare two climate projection layers side-by-side with an adjustable slider. They explored layer management features including opacity modification, legend viewing, zooming, duplicating, and removing layers. Additional tools tested included distance measurement, base map changes, screenshot capture, and screen recording.

Export Functionality Testing: The final phase involves accessing the Results section through the Jump to menu, visualizing project results, and downloading them in PDF format.

Detailed generic test scenario scripts are presented in **Table *5*** to 9.

Table 5. Generic DSS validation trial script 1 - Risk-Impact assessment (new)

No.	Prerequisites	Steps	Target	Expected behavior	Time	Notes
0	Credentials have been provided	**1. Login** From the landing page, click the "Sign in / Sign up" button located in the top-right corner or "Start now" Enter the credentials provided to you and log in. **2. Create a project** Once in the Project Manager, click "Create Project". Fill in the required fields and create the project. After creation, locate your project in the list and click on it to open. **3. Create a scenario** Inside the project, click the "New Scenario" button. Fill in all required fields and click "Save".	Authentication Project Manager	System successfully: → Signs the user in → Creates and saves new projects → Creates and saves new scenarios	≈3-5 min	**1.** The Project Manager remains accessible from the "Jump To" button on the header
1	User is logged in A project has been created A scenario has been created Sample data has been provided (optionally)	**1. Risk/Impact assessment** From the Project Manager, select a project from the list by clicking on it. Click on the "Edit" button on the created scenario for which to conduct the impact assessment. Select the tab labeled "Risk/Impact Assessment" which appears below your scenario. Following the provided instructions, upload data for Hazard, Exposure, Vulnerability Once all data is uploaded and validated, click "Submit Risk/Impact Assessment" to initiate impact calculation. **2. Monitor progress and view results** Monitor calculation progress via the R.I.A. Manager, located in the bottom-right corner and	Risk/Impact Assessment Data Visualization / Maps	System successfully: → Processes, validates and saves the uploaded data → Executes the impact assessment algorithm for the selected hazard/risk receptor pair → Returns a geospatial layer with the results of the impact assessment → Displays the risk/impact results on the map	≈10-15 min (depending on data size and upload speed)	**1.** It is possible to delete and re-upload the required data for an impact assessment for a given scenario **2.** In the map viewer you can temporarily disable or enable individual layers by the toggle button to reduce the number of active data layers on the same area

No.	Prerequisites	Steps	Target	Expected behavior	Time	Notes
		in the header. When the assessment is complete, click on the completed entry in the R.I.A. Manager. You will be redirected to the Map Viewer to see the results. **3. Explore the map and inspect data** Use click and drag to navigate the map. Zoom in/out using your mouse scroll wheel or the +/– buttons at the bottom right. Click on a data point in the relevant area of the map to open a popup showing the attribute table for that point.				

Table 6. Generic DSS validation trial script 2 - Resilience (new)

No.	Prerequisites	Steps	Target	Expected behavior	Time	Notes
0	Credentials have been provided	**1. Login** From the landing page, click the “Sign in / Sign up” button located in the top-right corner or "Start now" Enter the credentials provided to you and log in. **2. Create a project** Once in the Project Manager, click “Create Project”. Fill in the required fields and create the project. After creation, locate your project in the list and click on it to open. **3. Create a scenario** Inside the project, click the “New Scenario” button.	Authentication Project Manager	System successfully: → Signs the user in → Creates and saves new projects → Creates and saves new scenarios	≈3-5 minutes	**1.** The Project Manager remains accessible from the "Jump To" button on the header

No.	Prerequisites	Steps	Target	Expected behavior	Time	Notes
		Fill in all required fields and click "Save".				
1	User is logged in A project has been created A scenario has been created	**1. Resilience assessment** From the "Jump to" button in the header, select Resilience Assessment. Choose the Resilience Assessment Framework (RAF) option. Click "Create RAF" in the top-right corner to start a new assessment. Select the project and scenario you want to assess. Check the box to "Complete a new RAF Questionnaire" and click "Next". Fill in all questions in the questionnaire with appropriate responses. **2. View and download RAF results** Once the questionnaire is complete, click "View Result". Review the results displayed in the RAF donut chart. Download the chart in one of the available formats from the menu icon (3 horizontal lines) at the top right or the "Download" button at the bottom right of the chart. When finished, close the popup. **3. Change RAF results** From the three dots under the "Actions" column, click on the "Edit" button (on any of the completed assessments). Select "Complete a new RAF questionnaire" and click "Continue" to edit your submitted	Resilience Assessment Framework (RAF)	System successfully: → Provides targeted resilience results	≈8-12 minutes	**1.** To access the Resilience Assessment or functionality from the Project Manager, select a project from the list by clicking on it and then click on the "Edit" button on the desired scenario and navigate to the tab labeled "Resilience Assessment" appearing under the scenario information **2.** You can load an external assessment conducted in the LNEC RAF Tool by selecting "Add an External Assessment" instead of "Complete a new RAF Questionnaire "in Step 1 **3.** You can quickly view the RAF chart of a completed assessment from the three dots under the "Actions" column in the main RAF page, by clicking on "View RAF chart"

No.	Prerequisites	Steps	Target	Expected behavior	Time	Notes
		assessment. Make any necessary changes and click on "View Result" on the last question. Review the updated results displayed in the RAF donut chart.				
2	User is logged in A project has been created A scenario (with risk/impact assessment calculation completed) has been created	**1. Resilience assessment** From the "Jump to" button in the header, select Resilience Assessment. Choose the Resilience Assessment Framework (RAT) option. Select the project and scenario you want to assess. Click the "Create RAT" button to start a new assessment. Fill in all the information for each of the 5 questionnaires (Anticipation, Absorption, Coping, Restoration, Adaptation). **2. View and download RAT results** Once the assessment is complete, click "Save and Exit". Review the results displayed in the RAT radar chart, along with the Overall Resilience Index (ORI) score. Download the radar chart from the menu icon (3 horizontal lines) at the top right of the chart. **3. Change RAT results** Click on the pencil icon on any of the resilience metrics. Make the desired changes to your previously given answers. Click on "Save and Exit".	Resilience Assessment Tool (RAT)	System successfully: → Provides targeted resilience results	≈8-12 minutes	**1.** To access the Resilience Assessment or functionality from the Project Manager, select a project from the list by clicking on it and then click on the "Edit" button on the desired scenario and navigate to the tab labeled "Resilience Assessment" appearing under the scenario information

No.	Prerequisites	Steps	Target	Expected behavior	Time	Notes
		Review the changes on both the RAT radar plot and the ORI score.				

Table 7. Generic DSS validation trial script 3 - Adaptation (new)

No.	Prerequisites	Steps	Features tested	Expected behavior	Time required	Notes
0	Credentials have been provided	**1. Login** From the landing page, click the "Sign in / Sign up" button located in the top-right corner or "Start now" Enter the credentials provided to you and log in.	Authentication	System successfully: → Signs the user in	1 minute	**1.** The Project Manager remains accessible from the "Jump To" button on the header
1	User is logged in	**1. Review of existing measures** From the "Jump to" button in the header, select Adaptation Measures. Review the full list of adaptation measures from the table. Use the search bar or filters to narrow down the portfolio of available adaptation measures based on your preferences. Click the three dots under the "Actions" column and select "View", in order to review detailed specifications of selected measures in a popup. When finished, close the popup. **2. Creation of new measures** Click on "Create" button. Fill in all inputs included in the popup form and assign co-benefit measures. When finished, save the measure by clicking on "Create". The newly created measure is registered in the table along with the other measures.	Adaptation Measures	System successfully: → Implements discover and review of appropriate measures → Creates new adaptation measures → Compares adaptation measures → Prioritizes existing adaptation measures	≈8-10 minutes	**1.** To assign a measure to a scenario, click the three dots under the "Actions" column in the main Adaptation Measures page and select "Assign". Choose the appropriate project and scenario from the dropdown lists. Confirm the assignment by clicking "Assign". It is essential to have created at least 1 project/scenario in this case.

No.	Prerequisites	Steps	Features tested	Expected behavior	Time required	Notes
		3. Comparison of 2 measures Click on "Compare" button. Select 2 measures from the table, by checking the relevant boxes that have appeared next to the Title column. Review the details of the 2 measures side-by-side in a popup. When finished, click "Finish". Click on "Compare" button again to exit the mode. **4. Prioritization of measures** Click on "Prioritize" button. Select the climate hazard, cost and up to 5 co-benefits by checking their boxes on the side and then adjusting their weights. When finished, click "priorities". Review the updated measures table, showing only the entries that match your inputs and in a hierarchical order from most to least relevant based on the criteria set. Click "Clear filters" to exit the mode.				

Table 8. Generic DSS validation trial script 4 - Adaptation (new)

No.	Prerequisites	Steps	Features tested	Expected behavior	Time required	Notes
0	Credentials have been provided	**1. Login** 1. From the landing page, click the “Sign in / Sign up” button located in the top-right corner or "Start now" 2. Enter the credentials provided to you and log in.	Authentication	System successfully: → Signs the user in	1 minute	**1.** The Project Manager remains accessible from the "Jump To" button on the header
1	User is logged in	**1.Add climate projection layers in the map viewer** 1. Navigate to the Map Viewer from the "Jump to" button in the header. 2. Click “Add Layer” at the top-left and navigate the catalogue of available ICARIA layers by clicking on the folders. 3. Select the desired layers by clicking “Add” next to each one. 4. Close the catalogue window once done. All added layers will be listed on the left panel and active on the map. **2. Explore the map and inspect data**	Data Visualization / Maps	System successfully: → Allows loading and selection of climate projections → Offers the ability to compare climate projection layers side-by-side → Offers measurement tools for holistic spatial understanding → Extracts information for use in external communications or reports	≈8-10 minutes	**1.** If multiple layers have been selected, from the list of added layers on the left panel, click and drag a layer (up or down) to change the order of appearance on the map. The topmost layer on the left panel will be overlayed on top of all other layers on the map **2.** Use the toggle button next to each layer to enable or disable it from appearing on the map

No.	Prerequisites	Steps	Features tested	Expected behavior	Time required	Notes
		1. Use click and drag to navigate the map. 2. Zoom in/out using your mouse scroll wheel or the +/– buttons at the bottom right. 3. Click on the map icon on the right to change your preferred basemap. 4. Click on a data point in the relevant area of the map to open a popup showing the attribute table for that point (when at least 1 layer is active). **3. Compare data** 1. To compare two climate projection layers, click on the Split view button on the right side of the screen. 2. Once activated, select two layers to proceed with the comparison by clicking on the icon with the circles appearing next to each layer on the left panel. The two layers will be placed each on one side of the map.				**3**. Use the "Disable" button from the left panel to quickly clear (deactivate) the map of all active layers **4.** Use the "Expand" button from the left panel to quickly see the details of all loaded layers, such as legends and the opacity slider. Alternatively, expand each layer individually from the arrow icon. **5.** Use the "Remove" button from the left panel to quickly remove all loaded layers form the list **6**. Click on the full screen icon next to the layers list on the left side of the screen to view the map in full scaling

No.	Prerequisites	Steps	Features tested	Expected behavior	Time required	Notes
		3. Drag the slider left or right to expose more data on either side. **4. Measurement tools** 1. Click on any of the 3 icons on the top of the screen to measure distance, radius and area respectively. 2. Click once to add points to your measurement (for distance and area). 3. Click twice to save the measurement (for distance and area). 4. Deselect the clicked icon to exit the measurement process and right click on top of a measurement to delete it from the map (if needed). **5. Export** 1. From the buttons on the right side of the screen, click on the Record or Screenshot options to document what is rendered on the map for external use.				

Table 9. *Generic DSS validation trial script 5 - Decision Support (new)*

No.	Prerequisites	Steps	Features tested	Expected behavior	Time required	Notes
0	Credentials have been provided	**1. Login** From the landing page, click the “Sign in / Sign up” button located in the top-right corner or "Start now" Enter the credentials provided to you and log in. **2. Create a project** Once in the Project Manager, click “Create Project”. Fill in the required fields and create the project. After creation, locate your project in the list and click on it to open. **3. Create a scenario** Inside the project, click the “New Scenario” button. Fill in all required fields and click “Save”.	Authentication Project Manager	System successfully: → Signs the user in → Creates and saves new projects → Creates and saves new scenarios	≈3-5 minutes	**1.** The Project Manager remains accessible from the "Jump To" button on the header
1	User is logged in A project has been created A scenario has been created	**1. Review of results** From the "Jump to" button in the header, select Results. View the table listing all created projects. Click the "View" icon of a specific project under the Actions column. A new tab with the detailed results for the selected project opens.	Reporting	System successfully: → Generates report providing a review of results per scenario and project	≈3-5 minutes	**1.** Alternatively, to access the report from the Project Manager, select a project from the list by clicking on it and then click on the "View Final Report".

No.	Prerequisites	Steps	Features tested	Expected behavior	Time required	Notes
		Review the summarized results of all scenarios within that project across major categories (Risk/Impact Assessment, Resilience Assessment, Adaptation Measures). Download the report in PDF				

3.3.5 ICARIA trial solutions

In principle, the solutions presented in deliverable D4.1 are still the ones that were trialed in the end. However, the emphasis changed so that the DSS became a primary trial target, and the RAF and RAT were validated through separate events that did not fully follow the trialing methodology.

This is less of a limitation that it may appear at first because ICARIA DSS interfaces all other ICARIA solutions. However, it demonstrates the error we made in the beginning, when each piece of the software was presented as a separate solution that needs to be trialed, rather than concentrating on the features of ICARIA solutions we are really interested in validating.

3.4 Trial-specific trial scenarios

Three ICARIA trials all follow a generic trial scenario defined in section 3.3. However, each region has a different climatic and socioeconomic context. Consequently, three region-specific trial scenarios were developed, as "profiles" of the generic ICARIA trial scenario. Moreover, the trial scripts, presentations and survey questions were not only adjusted to the trial context but also translated to a language the regional stakeholders are most familiar with - Spanish (AMB trial), German (SBG trial) and Greek (SAR trial).

RAF and RAT were tested prior to the main trial event and the results are reported in Brito et al., 2024, and Cruz et al., 2024. Detailed results on ICARIA RAF and RAT trials are presented in Brito et al., 2026.

3.5.1 Summary of RAF/RAT testing findings

Guidelines for a performing resilience assessment using the RAF were proposed and were used by AMB. A pilot application of the RAT to SLZ case study was also made.

A preliminary version of the RAF was accessed by AMB partners and validated, namely regarding its relevance and data availability, detection of inaccuracies, barriers and limitations, and possible improvements. Overall, the following was noted:

- Clear communication is essential for regional assessments involving many stakeholders across multiple municipalities.
- Because regional assessments are complex and use varied data, reducing the number of essential metrics may be necessary.
- Given the diversity of natural areas, it may be best to group similar sites (e.g., beaches, parks, farms, caves) or analyze them separately before combining results.

Stakeholders in the case studies, in working sessions, responded to the metrics, and the tools integrate information and extract what is relevant to enable a structured assessment.

Following the RAF guidelines (Brito et al., 2026), AMB progressed from an essential to a comprehensive assessment. Overall, almost 1/3 of the metrics are classified as *advanced* or *progressing*. As an example, synthetic results for the resilience assessment of the Natural Areas in AMB are presented in **Figure 3**. Several aspects are *advanced*, but there is still room for improvement. Although there is no strategic plan for beaches, they are managed by a designated entity with regular maintenance and a dedicated budget, and CC and resilience are considered in planning. Beaches provide multiple ecosystem services (sports, culture, recreation, and biodiversity), but these are not currently monitored. Although no formal risk assessment was made, critical assets and protective buffers have been identified. CC impacts are expected, and several adaptation and mitigation measures are already in place. Results are thoroughly explored in Brito et al., 2026.

SLR assessed its resilience capabilities regarding electrical infrastructure. Synthetic results are presented in **Figure *3***. With several resilience aspects to tackle, absorption of CC impacts seem to be the most challenging.

(a) (b)

Figure 3. (a) Holistic resilience assessment in AMB Natural Areas and (b) Exploratory resilience assessment of critical energy assets in SLZ (Brito et al., 2026)

3.4.1 AMB Trial

The Trial for the **AMB CS** took place in **Barcelona on October 30th, 2025**. The primary objective was to present the scientific outcomes of Task 4.2 and, secondly, to test the performance and usability of the ICARIA DSS with relevant stakeholders

The entire workshop was centered on the **multi-perspective risk assessment of pluvial floods** on properties of the AMB.

Participant Selection and Composition

According to the ICARIA Trial planning in Deliverables 4.1 and 5.4 (Havlik et al., 2024; Truchi et al., 2023), the participants of the event were the stakeholders of the Community of Practice of the AMB CS. AQUATEC, Universitat Politècnica de Catalunya, and Area Metropolitana de Barcelona were the trial coordinators. The rest of the participants were as follows:

CONSORTIUM MEMBERS

- IREC: Catalonia Institute for Energy Research. A public research center ascribed to the Department of Climate Action, Food and Rural Agenda of the Generalitat de Catalunya
- CETAQUA: A public-private collaboration working on R&D&I solutions on sustainability and efficiency of the water cycle.
- FIC: A non-profit, private and totally independent entity with a focus on research in the field of climate change.
- Aigües de Barcelona: Public-private company which manages the water cycle in the AMB

EXTERNAL 3rd PARTIES

- Servei Meteorològic de Catalunya: A public company that provides meteorological information to Catalunya
- Consorcio de Compensación de Seguros: A public company managing insurance
- Oficina Catalana del Canvi Climàtic: An office in Catalunya dedicated to Climate Change and resilience
- TERSA: A company dedicated to waste management
- Protecció Civil: A part of the government dedicated to preparing communities in case of any kind of hazards
- Ecoparc: A waste management service with important infrastructure in the studied area
- TMB (Transports Metropolitans de Barcelona): A public transport company for the Barcelona Metropolitan Area
- Endesa: An energy management and service company

Event Structure and Agenda

As portrayed in ***Figure 4***, the AMB CS Trial ran from 09:45 to 14:00, providing a condensed and complete hands-on evaluation experience.

Agenda

9:45 – 10:00	Arrival of participants
10:00 – 10:20	Welcome and introduction of the meeting
10:20 – 10:45	Presentation of flood study results
10:45 – 11:00	Preparation for the participatory evaluation of the Decision Support System
11:00 – 12:00	Part 1 of the participatory evaluation
12:00 – 12:30	Break
12:30 – 13:30	Part 2 of the participatory evaluation
13:30 – 14:00	Conclusions and closing of the meeting

Figure 4. Official agenda for the AMB CS Trial

The event began with a welcome and introduction which provided a comprehensive overview of the ICARIA project, including its consortium, case studies, modelling tools, implementation and replication, and CoP workshops.

Following this introduction, the flood study results focused on the AMB case study were presented. They showcased preliminary results from high-resolution metropolitan flood hazard maps, generated using a calibrated coupled 1D/2D model.

The participatory evaluation of the DSS tool was conducted in two main sections. Participants were first briefed on the tool's activities and functionalities. They were then divided into **four groups** and provided with **detailed scripts to guide their testing of the ICARIA DSS**. In the first section (11:00-12:00), participants tested the Risk Impact/Assessment tool and Resilience Assessment surveys. After a 30-minute break, the second section (12:30-13:30) focused on testing the Adaptation Measures and Map Viewer features, with additional time allocated for free exploration of the tool.

The event concluded with participants completing a feedback survey designed to gather insights for improving the DSS tool.

Event Preparation and Logistics

The event was organized in consecutive steps to ensure everything worked smoothly. The steps were as follows:

- Script preparation: A thorough script for the exploration of the tool was designed and written by DRAXIS and AQUATEC (section 3.4.4), translated to Spanish and adjusted for use in the trial by turning it into a tutorial for the hands-on trial session with step-by-step instructions.
- Reviewing the DSS functions: By following the previously mentioned script and working alongside DRAXIS, there were multiple reviews of the tool until everything worked well.
- Creation of IDs for participants: In order to carry on the trial, five new IDs for logging into the tool were created
- Preparation of data: The datasets necessary for testing the DSS were prepared according to the ICARIA methodology. These included information for three different scenarios (baseline, business as usual and adaptation). The area selected was limited to only Barcelona instead of the whole Metropolitan Area. This decision to reduce the domain for this activity prevented the saturation of the DSS tool at the time of the trial. Scenarios were also created in the tool itself and shared with participants for viewing.

Data Provision and Materials

To carry out the trial efficiently, organizers provided each participant with the necessary data. This included a .txt file with the credentials for login, and several files needed for the Risk/Impact Assessment:

- **Hazard data layer:** Containing water depth and speed information for the area of Barcelona.
- **Exposure data layer:** Containing information about building height and main use
- **Area segregation data layer:** With defined neighborhoods that were used to present results grouped by area
- **Cost and permeability curves:** Used to calculate the damage to properties

Observation and Feedback Collection

The trial of ICARIA's Decision Support System (DSS) was organized as a guided hands-on session where participants followed a structured workflow to test the tool's main functionalities of ICARIA DSS.

Participants with the tester role accessed the tool at https://icaria.draxis.gr using the provided credentials. and followed the provided script independently. Throughout the trial, they used a **shared project with pre-calculated results** to expedite certain processes and demonstrate full functionality without waiting for lengthy calculations. The trial was designed to be time-efficient while covering all major components of the DSS tool.

During the trial, the participants with the observer role had the responsibility to complete the "**observer questionnaire**" designed to collect information on the performance of participants with the tool and, thus, the usability of the tool itself.

Once the trial was concluded, participants were asked to answer a **short survey** prepared to learn more about their opinions on the tool and possible improvements.

3.4.2 SBG Trial

The fourth Austrian CoP meeting took place on November the 18th 2025, in the city of Salzburg, with a primary goal of validating the ICARIA DSS through a trial. This meeting has brought together a diverse group of regional experts and end-users, underscoring the collaborative nature of the ICARIA project.

The trial was designed around two predefined scenarios. The first scenario focused on **flooding events, and their impacts on the residential buildings**, while the second addressed **storm events and their potential impacts on electricity distribution**, with particular emphasis on electricity infrastructure such as distribution networks and power poles.

Participant Selection and Composition

The invited stakeholders were part of the group of the Community of Practice of the SBG CS. AIT was the trial coordinator, the rest of the participants were:

CONSORTIUM MEMBERS

- VERBUND, Hydropower provider: The hydrological service observes, researchers, analyzes and keeps evidence of the basic data of the quantitative water cycle.

EXTERNAL 3rd PARTIES

- State of Salzburg (Forestry Service, Water Management, Hydrology, Disaster Management)
- SIR (Salzburg Institute for Regional Planning & Housing), dealing with topics: Communal and regional development, climate adaptation, energy and climate planning

- City of Salzburg
- KLAR! Pinzgau (Climate Change Adaptation Region), The "Climate and Energy Model Regions" program, funded by the Austrian Climate and Energy Fund, supports Austrian regions at an early stage with its "Climate Change Adaptation Model Regions" (KLAR!) funding program. This helps to reduce damage and exploit opportunities.

Event Structure and Agenda

As depicted in **Table *10***, the SZB CS Trial ran from 13:0 to 16:00. The agenda and the duration were carefully agreed upon with the stakeholders, to respect their obligations related to daily responsibilities and schedules.

Table 10. Official agenda for the SBG CS Trial

4th CoP Workshop –Salzburg CS November the 18th 2025	
Hour	**Activity**
13:00 – 13:15	Welcome & round of introductions
13:15 – 13:45	Project overview, review of past CoP, results & decision support system
13:45 – 14:45	Test run of decision support system
14:45 – 15:00	Coffee break
15:00 – 15:45	Test run of decision support system
15:45 – 16:00	Next steps & farewell

Upon arrival at the workshop location, the session was formally initiated with an **introductory presentation**. Participants were provided with an overview of the recent developments within the ICARIA project, with a particular focus on progress achieved in the months following the previous meeting with stakeholders. This introduction aimed to reestablish a shared understanding of the project context and objectives before commencing the trial activities.

AIT colleagues presented the **current status of the project**, including updates on system development and the state of ongoing analyses. These updates covered several key areas, such as **climate change related assessments**, the acquisition and integration of new **datasets**, and the evaluation of different **scenarios**. In addition, **potential impacts** derived from EU-level data and analyses were discussed, with specific reference to their relevance for the Salzburg region as the defined area of interest. An **introduction to the ICARIA DSS** was provided, as well as an overview of what was planned to be done in the practical phase of the trial. For this purpose, a set of slides such as one in **Figure *5*** were created and presented (REF).

Following the introductory presentations, the trial transitioned into its practical phase. Participants were divided into two groups to facilitate **hands-on interaction and structured engagement** during the trial. Within each group, stakeholders were assigned specific roles corresponding to the tasks and responsibilities they would assume during the trial execution. This **role-based setup** was intended to mirror realistic usage scenarios and to support a comprehensive evaluation of the system under representative conditions.

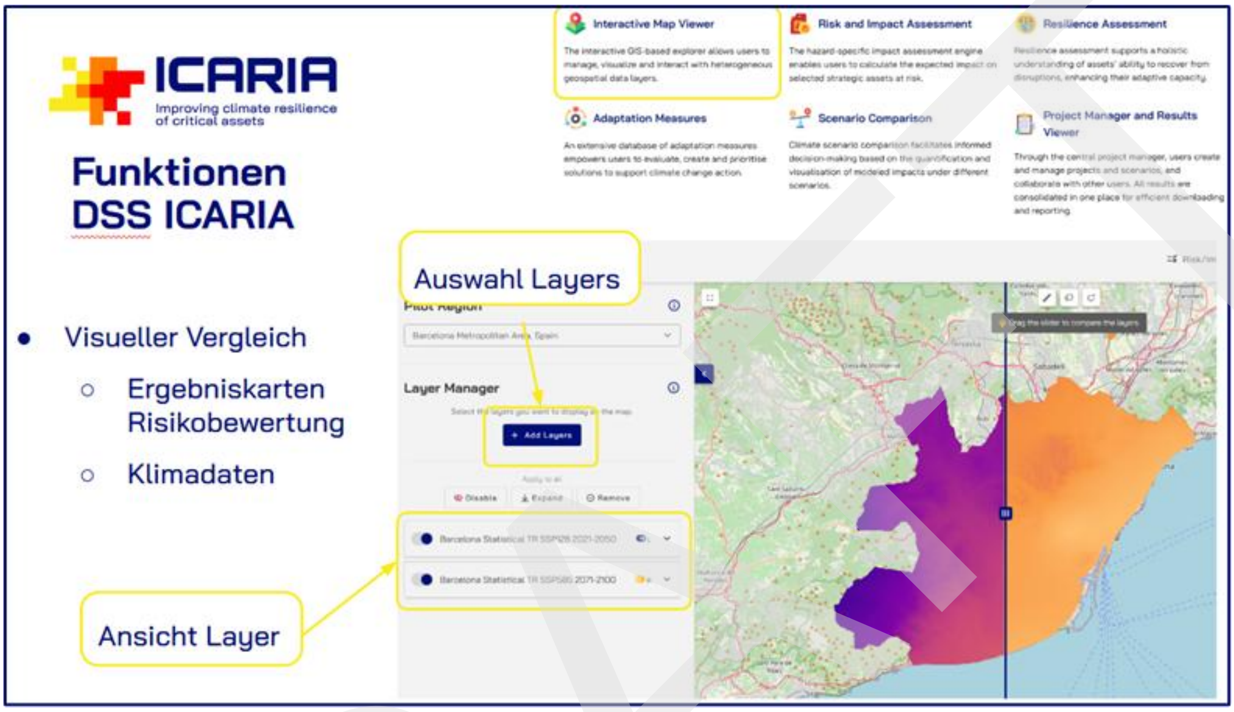


Figure 5. Slide from "Introduction to ICARIA DSS presentation"

Dry Runs, Event Preparation, and Logistics

With the objective of being as well prepared as possible for the trial and of avoiding potential technical or organizational issues during the trial event, a series of preparatory activities were carried out well in advance. These activities were designed to ensure that all materials, processes, and infrastructure were ready and fully validated prior to the trial.

A couple of months before the trial took place, we began by establishing all required materials. For example, generic ICARIA trial scripts were adopted to the trial context and transformed into detailed **step-by-step procedures** that participants were asked to follow during the trial. Trial scripts, as well as related presentations and data collection materials (surveys and reporting templates) were put in the trial context were all translated to German language, to support the evaluation of the ICARIA project's decision support system prototype by Austrian stakeholders. In parallel, a predefined set of **datasets intended for use during the trial** was prepared and initialized.

To validate both the scripts and the technical setup, multiple **dry runs** were conducted by the project team in the months leading up to the trial. These dry runs were designed to closely replicate the conditions and activities planned for the actual trial day. During each dry run, we assessed whether the step-by-step instructions were sufficiently clear and whether users could complete the required tasks without ambiguity or difficulty. Any issues identified—such as unclear instructions or workflow inefficiencies, were systematically addressed, and the scripts were updated and refined after each iteration. The dry runs also served to test and improve the decision support system prototype itself. Issues encountered during activities such as dataset uploads or system interactions were documented and communicated to DRAXIS who were responsible for the prototype's development. They provided timely support by implementing improvements and resolving technical issues as they were identified, enabling continuous enhancement of the system throughout the preparation phase.

In addition, the dry runs were used to evaluate the overall trial agenda and time allocation. We initially aimed for a **trial event duration of four to five hours**, allowing sufficient time not only for hands-on testing of the prototype but also for in-depth discussions with stakeholders, as well as to provide the participants adequate time to complete questionnaires and provide detailed feedback to support subsequent analysis. This was later **reduced to 3 hours,** due to stakeholders' daily responsibilities.

These iterative dry runs ultimately contributed to the refinement of all components required for the trial conducted in Salzburg in November, including **content, workflows, and logistics**. From an infrastructure perspective, DRAXIS provided **user accounts** to enable system access, while AIT supplied the necessary local **hardware**, including laptops, external screens, cables, mice, tablets, and **printed copies of the step-by-step scripts**. As a result of these comprehensive preparations, all technical and organizational elements were in place prior to the trial. This ensured that participants could focus exclusively on using the preconfigured systems and materials, without the need to address setup or operational concerns during the event.

Trial Script

The Trial Script distributed for the workshop served as a structured guide to be followed during the workshop trial process. It was based on generic scripts presented in section 4.4.4 and adjusted for the trial context (hazards, elements at risk, location, risk type) to support the evaluation of ICARIA Decision Support System within the broader context of anticipated future use cases. Particular attention was given to the **flood hazard and its impact on the electricity grid and energy supply, within the current and potential Climate change scenarios.**

The trial scenario framework incorporated defined reference datasets and reflected recommendations provided by the responsible experts (e.g., from AIT) and through earlier conversations and workshop exchanges with the stakeholders. These recommendations outlined the sequence of steps that were to be executed within the DSS prototype, such as opening and managing the required files and folders. To ensure accessibility and alignment with the local context, the **script text was translated into German, adequate screenshots of the relevant DSS views were integrated, and the whole document printed for easier handling**.

From a functional perspective, the generic Trial Script was transformed into an easy to follow a step-by-step tutorial with illustrations of expected results. Resulting tutorial script is designed to be executable by trial participants with varying levels of prior experience, with little or no support from the trial organizers. While simplified, it still covers all necessary operational aspects, such as data preparation, processing, and result validation.

The script follows a step-by-step structure from generic scripts (Section 4.4.4) as much as possible, but with simplifications to accommodate for the shorter trial event duration. The script begins by signing up, creating a project and establishing a baseline scenario. Subsequent steps guide them through the definition of additional scenarios, the identification of required quantitative and qualitative data for analysis, and the methods for evaluating and validating results.

SBG Trial Script was provided to workshop attendees largely in its finalized form. However, its development was iterative. Initial versions were drafted based on generic scripts. Through dry runs, the script underwent several rounds of testing and refinement before converging on the final version presented at the workshop in November. Most notably, the visual representation of anticipated results was added for every major work step to ease the execution.

Data Provision and Materials

In line with the selected trial context, the required data sets were prepared and made available in the laptops for easy access for participants. For both trial scenarios, dedicated **hazard and exposure data sets** were created to support the analysis and execution of the trial and perform the impact assessment activities associated with this scenario. An overview of these files is provided in the list below:

For the **storm event**, the provided datasets included hazard data detailing **wind speed and wind direction**, geographically distributed across the defined area of interest. In addition, an exposure dataset was provided, containing information on the **geographic location of the electricity towers**.

- vmax_gust_event.tif (expected wind speeds)
- vmax_gust_highest_values.tif (another file with simulated high-wind speeds)
- towers.zip (Electricity Towers)

For the **flooding event**, the datasets included hazard data describing **expected flood depths** under different scenarios, with return periods of 2, 30, and 100 years. These datasets represent anticipated flooding conditions and their spatial distribution. In addition, an exposure dataset was used, consisting of **building data** sourced from OpenStreetMap.

- flooddepth_ssp585_2y.zip
- flooddepth_ssp585_30y.zip
- flooddepth_ssp585_100y.zip
- osm_buildings_mittersil.zip

Observer and Feedback Collection - The Approach

To collect structured feedback from stakeholders, eight external trial participants were divided into two groups, each with access to the DSS prototype. Within each group, one participant was responsible for executing commands and interacting directly with the prototype. A second participant guided the process by following the trial script, reading the instructions aloud, and providing verbal guidance to the person operating the system. The two remaining persons were assigned a role of observers. Their role was to monitor the trial execution and respond to a predefined set of questions using tablets

The **Observer questionnaire** focused on specific steps performed during the trial, such as the perceived simplicity or difficulty of tasks like uploading exposure datasets into the. Feedback collected through these structured questionnaires constituted the primary source of step-level usability insights. **Additional feedback** was intended to be collected at the end of the workshop through a live Mentimeter session, using **higher-level, reflective questions**. However, due to time constraints, this live session could not be conducted. Instead, the same set of questions was subsequently distributed to participants via email in an adapted, non-live format, allowing feedback to be gathered asynchronously.

Finally, **qualitative feedback** was also collected through direct discussions between AIT project members and stakeholders during the trial. These informal exchanges provided valuable contextual insights and complemented the structured questionnaire-based feedback.

3.4.3 SAR Trial

The Trial for the SAR CS took place in Rhodes Island on December 12th, 2025. The primary objective was to present the scientific outcomes of Task 4.2, and secondly to test the performance and usability of the ICARIA DSS with relevant stakeholders.

The entire workshop was centered on the **multi-perspective risk assessment of wildfires, tested on Rhodes Island, and the heatwave for Syros. Moreover, the flood risk assessment methodology using ICARIA DSS, for the mini-trial on Naxos, was presented to the CoP**.

Participant Selection and Composition

According to the ICARIA Trial, as outlined in Deliverables 4.1 (REF) and 5.4 (REF), the participants in the event were stakeholders in the SAR CS Community of Practice (CoP). The National Center of Scientific Research "Demokritos" (DMKTS) and the South Aegean Region (SAR) were the trial coordinators. The remaining participants were as follows:

CONSORTIUM MEMBERS

- DMKTS: National Center for Scientific Research "Demokritos". Public research centre, affiliated to the Ministry of Development.
- SAR: South Aegean Regional Authority

EXTERNAL 3rd PARTIES

- READ S/A: Public-private company which manages the EU projects of SAR
- Ministry of Health: General Hospital of Rhodes
- Region of South Aegean - Civil Protection department
- Ministry of Civil Protection: Fire Service of Rhodes
- Municipality of Rhodes - department of Civil Protection
- Hellenic Coast Guard
- Chamber of Commerce of Rhodes
- Rhodes Hotel Association

Event Structure and Agenda

As shown in **Figure *6***, the SAR CS Trial ran from 12:00 to 16:00, providing a condensed and comprehensive hands-on evaluation.

Agenda	
12:00 – 12:15	Registration
12:15 – 12:30	Welcome and introduction to ICARIA project
12:30 – 13:15	Presentation of the Wildfire risk assessment methodology e.g. Rhodes
13:15 – 13:45	Presentation of the Heatwave risk assessment methodology e.g. Syros
13:45 – 14:00	Presentation of the Flooding impact assessment methodology e.g. Naxos
14:00 – 14:30	Lunch break
14:30 - 15:30	Implementation of scenarios in the DSS
15:30 – 16:00	Closing remarks and DSS evaluation

Figure 6. Official agenda for the SAR CS Trial

The event is a half-day ICARIA project workshop running from 12:00 to 16:00, beginning with participant registration and a short welcome and introduction to the project, followed by successive presentations of the wildfire risk assessment methodology using Rhodes as an example, the heatwave risk assessment methodology using Syros, and the flooding impact assessment methodology using

Naxos, then a lunch break, after which participants work on the implementation of scenarios in the decision support system (DSS), and the event closes with final remarks and an evaluation of the DSS by attendees.

Event Preparation and Logistics

The event was organized in consecutive steps to ensure everything worked smoothly. The steps were as follows:

- Script preparation: A thorough script for the exploration of the tool was designed and written by DRAXIS (section 3.4.4), translated to Greek and adjusted for use in the trial by turning it into a tutorial for the hands-on trial session with step-by-step instructions.
- Reviewing the DSS functions: By following the previously mentioned script and working alongside DRAXIS, there were multiple reviews of the tool until everything worked well.
- In order to carry on the trial, the participants used the DMKTS IDs for logging, due the absence of additional computers in the meeting location.
- Preparation of data: The datasets necessary for testing the DSS were prepared according to the ICARIA methodology. These included information for three different scenarios (baseline, business as usual and adaptation).

The trial of ICARIA's Decision Support System (DSS) was designed as a guided, hands-on session in which participants followed a structured workflow to test the tool's core functionalities. Participants accessed the tool at https://icaria.draxis.gr using the provided credentials. They created projects and scenarios in the Project Manager, including a scenario named 'Actual' to use throughout the trial.

During the trial, participants utilized a shared project with pre-calculated results to speed up specific tasks and showcase the tool's full capabilities without delays. The design prioritized time efficiency while ensuring all key features of the DSS tool were covered.

Data Provision and Materials

To carry out the trial efficiently, organizers provided each participant with the necessary data for the Trial region. Only the wildfire risk assessment tool was placed on the DSS, while the Heatwave assessment was performed offline.

The files needed for the Risk/Impact Assessment were:

- **Hazard data layer:** FWI gridded data for the Rhodes Trial area.
- **Exposure data layer**: Generated from the Hazard map and the CLC data (Copernicus). The fuel type map is included on the DSS. Observation and Feedback Collection

Once the trial was concluded, participants were asked to answer a short survey prepared to learn more about their opinions on the tool and possible improvements. The survey was prepared by DRAXIS and translated into Greek by DMKTS.

3.5 Trial Results: validation by stakeholders

3.5.1 AMB Trial

The primary objective of this trial event was to collect comprehensive feedback from participants regarding the Decision Support System (DSS) prototype. Recognizing the critical importance of user input in the development process, a multi-faceted feedback collection strategy to ensure thorough and diverse insights was implemented. This approach combined three distinct methodologies: first, participants were invited to complete a structured survey that captured their impressions, ratings, and suggestions for improvement; second, an observer was assigned to monitor the proceedings systematically, documenting user interactions, challenges, and behavioral patterns in real-time; and third, direct feedback was gathered through interactive discussions and conversations with participants during and after the trial sessions.

Survey results

The survey conducted at the end of the trial was designed by AIT and replicated in all three trials equally. As reflected in **Figure 7**, the Trial participants covered a spectrum of profiles. One third were members of research institutions, one half belonged to technical departments of public administrations or infrastructure operators, and the remaining 18% were members of academia.

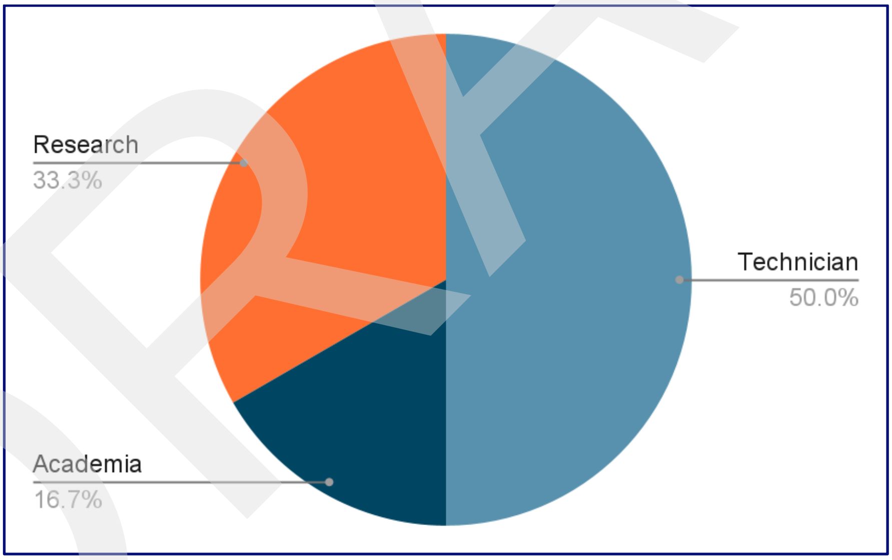
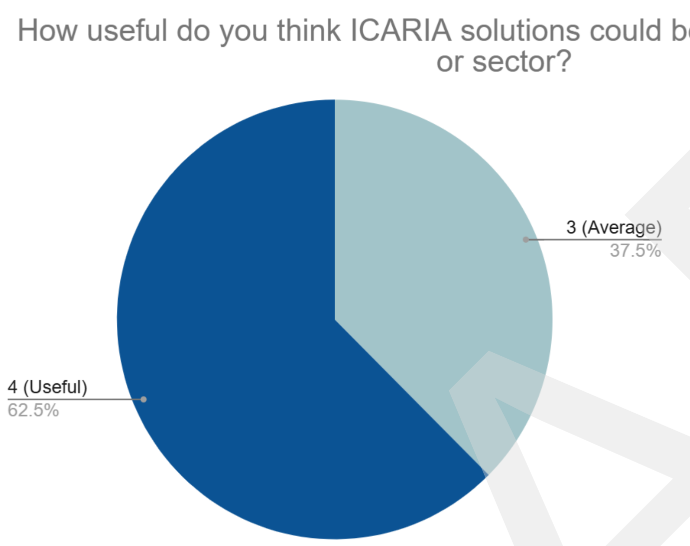


Figure 7. AMB Trial participants roles

On the next part of the questionnaire participants were asked for open-ended feedback such as key concepts that they associated with the tool or what parts of the tool they would improve, include or change.

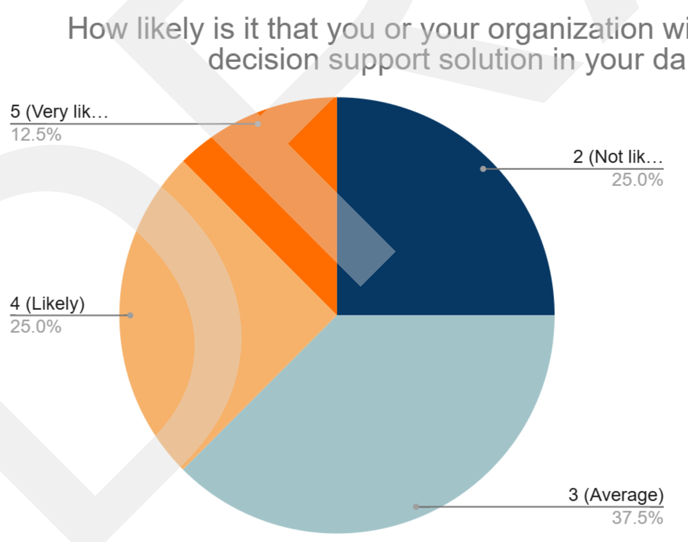
There was also quantitative feedback collected, reflected in the following graphs. Figure 8 summarizes participants' feedback on the usefulness of the ICARIA tools. Answers in general were positive (62,5% of participants consider the tool as useful) with a few still unsure of the tool's potential for their specific line of work. The next graph (**Figure *9***) reflects the variety of opinions on how likely it is for participants to apply the DSS tool in the future to their daily work. Here, most participants thought it was not probable that they would directly use the tool frequently. On the last question of the survey, represented by **Figure *10***, we can see most participants were satisfied with the tool and its opportunities even though they only had access to a first prototype which explains the average answers.



SCORE 3.6

Level of usability	Votes
1 (Not useful at all)	0%
2 (Not useful)	0%
3 (Average)	37.50%
4 (Useful)	62.50%
5 (Very useful)	0%

Figure 8. Answers to the question of usability of ICARIA solutions

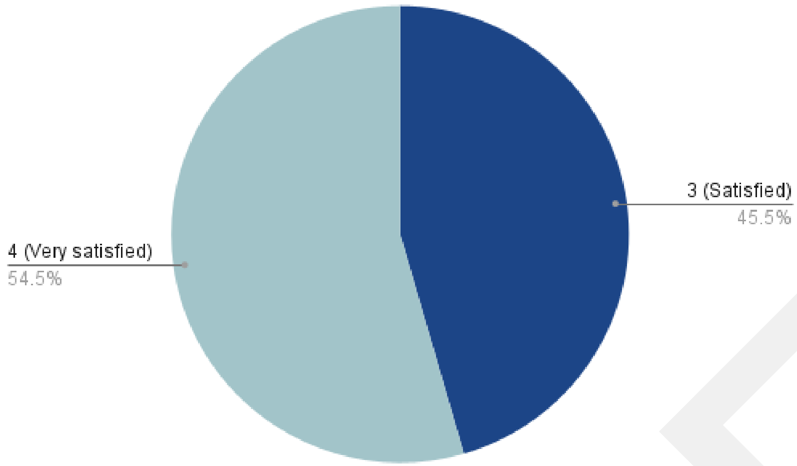


SCORE 3.3

Likeliness	Votes
1 (Not likely at all)	0%
2 (Not likely)	25%
3 (Average)	37.50%
4 (Likely)	25%
5 (Very likelyl)	12.50%

Figure 9. Answers to the question of applicability of the DSS tool to daily work.

How satisfied are you with the implementation of the ICARIA Decision Support System?



SCORE 3.5

Level of satisfaction	Votes
1 (Not satisfied at all)	0%
2 (Unsatisfied)	0%
3 (Satisfied)	45.50%
4 (Very satisfied)	54.50%
5 (Extremely satisfied)	0%

Figure 10. Answers to the question of satisfaction with the DSS tool.

Observer Findings

As part of the learning opportunities within this trial, a designated organizer participated as 'observer'. The role of this observer was to focus on the different user groups and record any difficulties encountered throughout the various processes. These observations were subsequently captured in a structured questionnaire, which resulted in the following insights.

Strengths:

- General navigation was easy and intuitive. Most sections received a low difficulty score.
- Mandatory fields on the Project Creation were clear to most participants.
- Scenario comparison rated the easiest and most engaging functionality. Users navigated tabs confidently.
- The process of updating Hazard, Exposure and Vulnerability data were generally clear and easily validated.
- Platform's flow and logical structure were appreciated
- Users recognized strong potential for use across different regions and organizations.

Weaknesses

- Around half of the users required some guidance to understand the RAF and RAT charts.
- Although the process of uploading data was clear, there was some difficulty understanding the type of data needed to carry out the assessment.
- Some of the map viewer's functionalities (zooming, split view, visualizing the attribute table…) were a little confusing for some participants.
- Transitions to different parts of the tool through the 'Jump to' button were not immediately intuitive.

In general, **participants could quite easily explore the tool in its totality with the help of the script. Most functionalities were intuitive and easy to understand** except for some specific ones which required more detailed explanation or guidance.

Feedback from participants

As previously mentioned, feedback was gathered in three different ways to provide a holistic view of the participants' interactions with the tool. At the end of the trial, discussions and conversations with participants provided some lessons learned which are as follows:

- Everyone present confirmed their interest in the information provided by the DSS, considering it relevant and actionable for a variety of sectors and users.
- Most participants were interested in using ICARIA's DSS services. There were also some doubts on how the prototype presented on the day of the trial would develop in the future. Participants expected these improvements to make the tool even more valuable for climate adaptation planning.
- Considering the prototype status of the DSS tool at the moment of the trial, participants recognized its potential and possibilities. The lines of work that intrigued most stakeholders were the development of interoperability and collaboration within the tool and the assessment of cascading effects.
- The section of stakeholders from the regional and local administrations as well as operators, found the Resilience Self-Assessment part of the tool particularly interesting. The RAF questionnaire was deemed useful for assessing and designing policies in the future by administrative roles. The RAT assessment was favored by operators and infrastructure managers.
- The need for expert knowledge was mentioned across all participants at some point during the trial. In particular, during the process of the Risk/Impact Assessment, it was difficult for them to understand how to prepare the necessary data for upload. They proposed to provide a clear, non-expert-friendly detailed guide to avoid needing the support of someone with significant technical expertise. This aspect was seen as the main setback for the tool.
- One of the key strengths of the DSS tool, as pointed out by the different feedback obtained, was the ability to easily compare multiple adaptation or hazard scenarios. Visualization of these scenarios with different climate projections was also very interesting for everyone.
- Participants were convinced that the tools resilience assessment functionalities were easily replicable to assets and regions beyond the AMB. Again, the opinion was that data availability and preparation were the main barrier for this.

3.5.2 SBG Trial

The objective of the SBG trial was to obtain structured feedback from relevant end users and stakeholders on the Decision Support System (DSS). Participants were first provided with an overview of the project status, the development progress of the tools, and the functionalities related to the DSS. They were also introduced to outputs from other tools, such as the RAT and RAF tools, which can be used to assess resilience in the context of climate change. The initial part of the workshop therefore focused on presenting the work completed so far and demonstrating the types of results these tools can generate.

The second and more interactive part of the trial allowed stakeholders to use the DSS prototype directly. For this interactive test run, the participants were divided into two groups and guided by a script to operate the DSS. The exercise involved several core functions of the tool, which includes calculating wind risk for electricity infrastructure, exploring the map view for climate risk maps, testing the Resilience Assessment Framework. They were able to explore several scenarios for the Mittersill area in the Land of Salzburg, assessing risk, preparedness, and potential climate-change impacts. The prototype enabled users to examine effects on critical infrastructure—particularly the electricity and energy systems, including transmission towers and masts. Stakeholders could upload relevant data (e.g., flood-risk maps), adjust parameters, and test different options. The DSS then processed these inputs and provided outputs such as heat maps, expected cost estimates, and object-level details through the system's interface. This hands-on use formed the core feedback component of the trial.

The same methodological approach that was introduced in the section 5.2.3 and elaborated for the AMB trial was also applied for the collection and analysis of user feedback in this trial. In total, three distinct feedback collection approaches were carried out with end users: observation, discussion and high-level questions in plenum.

Observation Findings

The first set of feedback was gathered during the trial and live demonstration sessions. Six **observers** monitored user interactions and collected structured feedback: two observers were assigned to each user group, with one additional non-stakeholder observer providing support as needed. Feedback was captured primarily through standardized questionnaires completed by the observers, which combined categorical responses (e.g., Yes/No) with Likert-scale items (1–5) to measure aspects such as ease of use and overall task clarity.

Consistent task sequence/script was followed by both groups to validate different features of the DSS, and through it also of the RAF, RAT and the portfolio of adaptation measures. Observers documented feedback for each step, such as uploading files or selecting scenarios, using targeted questions aligned with the task script. The collected data formed the primary basis for analysis - particularly for resolving the Ux type of questions.

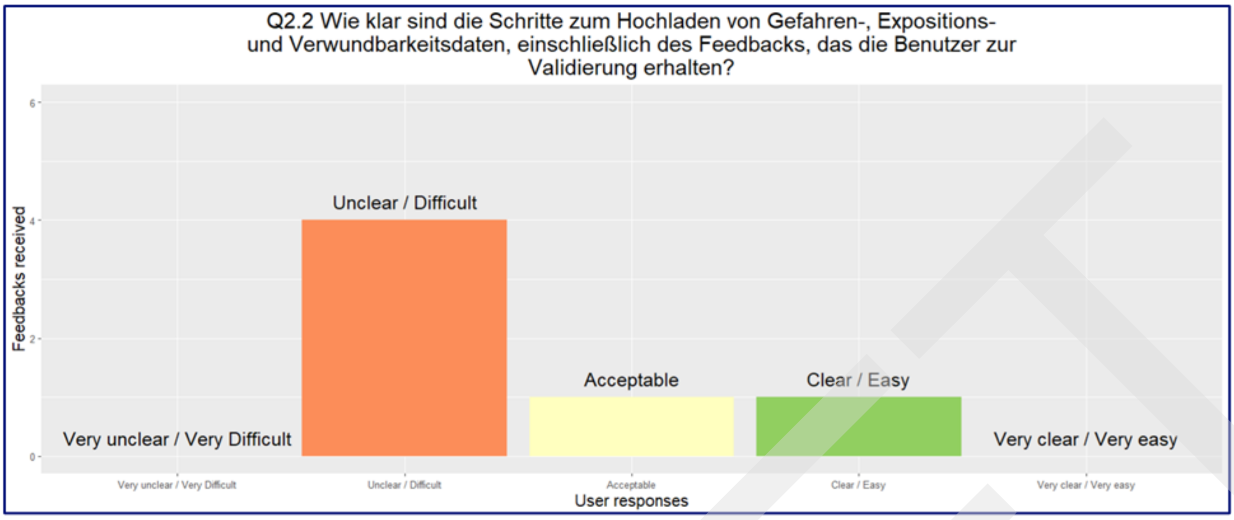


Figure 11. Answers to one of the trial questions

All collected data were systematically analyzed to identify recurring patterns and trends. Based on this analysis, key strengths and weaknesses were identified across the different operational steps of the prototype. These insights provide a structured basis for evaluating usability, clarity, and overall user experience, and they inform recommendations for future improvements, especially considering the potential stakeholders and end-users from the Land of Salzburg.

Strengths:

- General navigation becomes understandable once users are oriented, i.e., most sections were ultimately rated as manageable in terms of difficulty.
- Key entry points and primary actions (e.g., project creation, scenario setup, access to RIA and RAF) were generally discoverable without major blockers.
- The conceptual structure of projects, scenarios, assessments, and adaptation measures was clear to most users and aligned with expectations.
- Core analytical functionalities (climate projections, RAF diagrams, scenario comparison, reports) were perceived as powerful and valuable.
- Some users appreciated the flexibility and depth of the platform, particularly for complex analytical workflows.

Weaknesses:

- Feedback during long-running processes (saving, loading, calculations) was insufficient, leading to uncertainty about system status and results.
- Split map view and comparison functionalities were confusing, with users struggling to understand which datasets were being compared and how.
- Multi-step workflows, especially RAF questionnaires, were perceived as time-consuming and demanding in terms of thinking strongly what to select and answer.

- In some cases, the lack of contextual explanations (terminology, units, legends, attribute popups) caused hesitation and required external assistance.
- Navigation across modules (scenario setup, RIA, RAF) sometimes caused disorientation due to unclear process sequencing and missing orientation cues.

Plenum Feedback

We had planned to conduct a Mentimeter questionnaire to capture high-level end-user feedback and ideas during the trial. However, due to time constraints, it could not be administered in real-time. Instead, as previously noted, the questionnaire was sent to participants via email. Responses were collected asynchronously, and the following figures summarize the results obtained from this process.

The **workshop evaluation survey** provides insights into the perceived usefulness, maturity, and future development needs of the ICARIA Decision Support System (DSS). We received feedback from half of the participants, which clearly illustrates the advantage of data collection during the trial event, as opposed to a-posteriori surveying. Overall, the ICARIA solutions were positively assessed. Across all rating-based questions, responses consistently ranged from neutral to very positive, with no indication that the system was considered not useful. In particular, participants rated both the potential usefulness of the ICARIA DSS for their organization or sector and the likelihood of using such a decision-support tool in daily work towards the upper end of the scale, suggesting a clear interest in the approach.

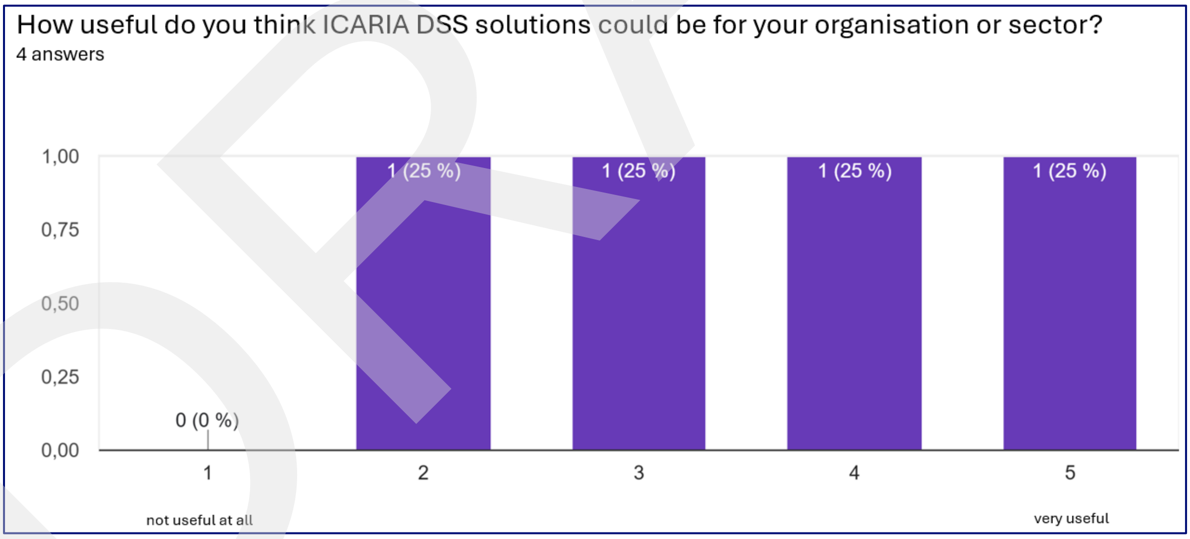


Figure 12. Answers to the question of usability of ICARIA solutions

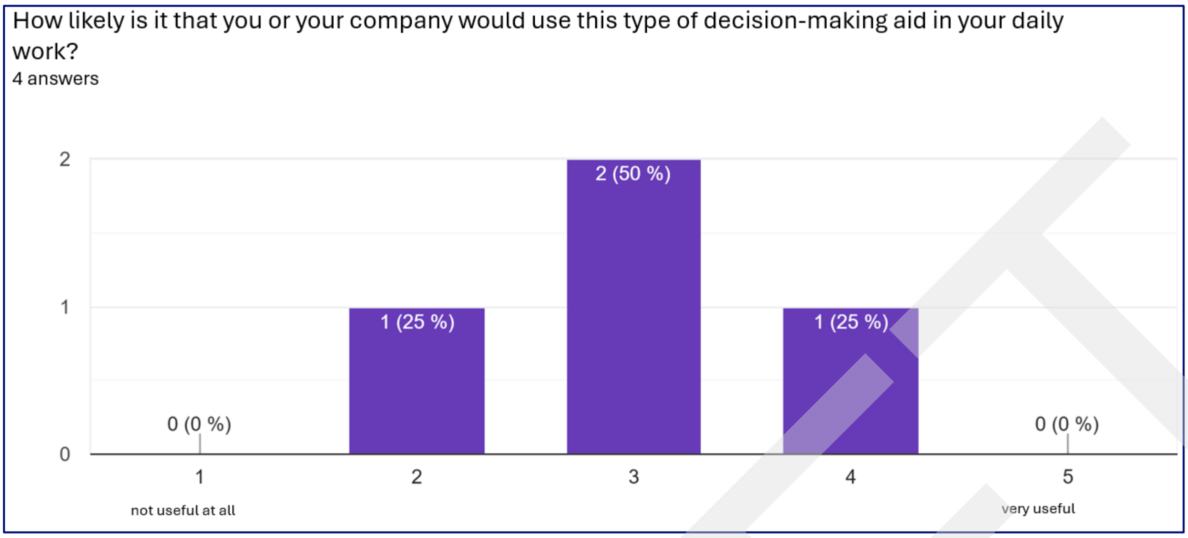


Figure 13. Answers to the question of satisfaction with the DSS tool.

Satisfaction with the current development status of the ICARIA DSS was generally high, although not without reservations. While the concept and objectives of the system are well received, the prototype is not yet perceived as fully ready for routine operational use.

The qualitative feedback further contextualizes these findings. Participants highlighted several areas for improvement related to usability and accessibility. Key suggestions included the provision of multilingual options (specifically German), clearer definitions of parameters and options, and the inclusion of concrete examples to support interpretation of results. Several respondents emphasized that greater transparency—such as making input parameters visible in reports—and a significantly simplified user interface would be critical for broader adoption beyond expert users.

Regarding future development priorities, participants consistently stressed the importance of risk- and hazard-related modelling aspects. Particular emphasis was placed on the treatment of multiple hazards and multiple risks, as well as on data quality and the integration of existing, verified datasets. Model transparency and practical orientation were also identified as essential factors for increasing trust and applicability.

In summary, the workshop results demonstrate strong conceptual support for the ICARIA DSS, coupled with clear expectations for simplification, improved transparency, and enhanced data and risk modelling to ensure practical usability in real-world decision-making contexts.

Discussions Feedback

Overall, the interest in the DSS was high and its usefulness acknowledged. However, the applicability of the RAF to rural areas was estimated to be low. An interesting discussion on the role and expectations from the EU projects emerged, reflecting on a discrepancy between the user's need for fully fledged products and modelling results that are tailored for their specific needs and the reality of the EU projects where new ideas and methodologies are explored, resulting in functional prototypes and only partial provision of the data and models the stakeholders need in their daily work. For example, the project has demonstrated that the risk of future storms directly affecting the electricity transport infrastructure is relatively small, due to geographic factors and resilience thereof. In discussion we realized that secondary damage could also occur, e.g., due to trees that are already weakened by drought and temperature-induced insects infestation falling over. This risk is highly dependent on the tree species, with at least one commercially exploited species being strongly affected by climate change. Unfortunately, modelling of this risk wasn't foreseen in the project and needs to be done in follow-up research projects or dedicated commercial studies.

3.5.3 SAR Trial

The main goal of this trial was to gather detailed feedback from participants on the Decision Support System (DSS) prototype and discuss the different scenarios and hazards for the Trial islands of SAR. The trial event focused on the usability of the DSS and the interest of the CoP on the hazards tested with it, the various hazards that potentially can be investigated and its adaptability to the rest of the hazards they proposed. To achieve the optimum result, like in the rest of the Trial events, and based on the Trial structure of AMB trial, the events combined three methods:

- Survey based on the user impressions
- Monitored and guided session on the use of the DSS
- Real-time feedback and discussion on the DSS and the risk assessment methodologies for the two islands

Survey results

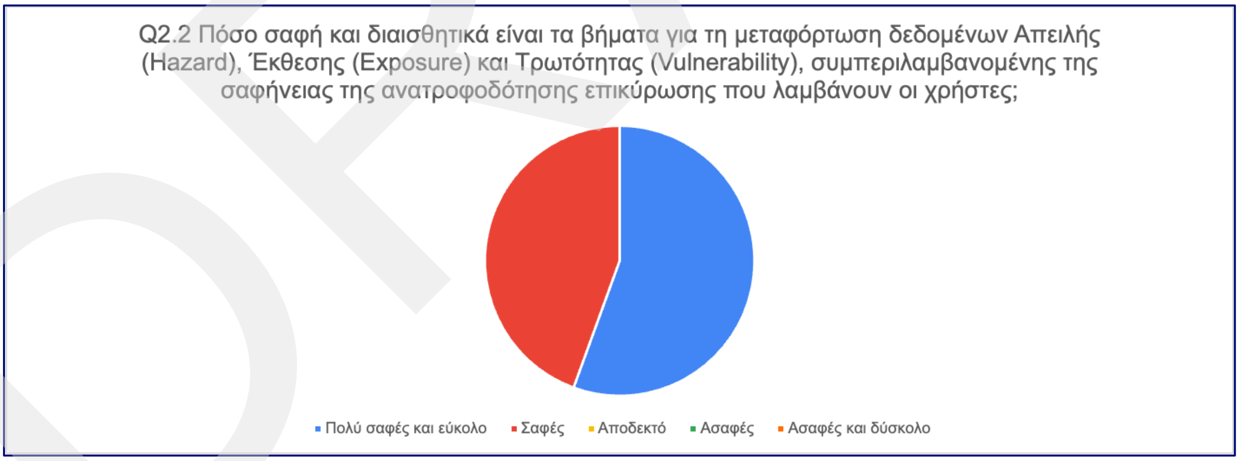


Figure 14. Answers to the question of the user experience on data loading and user feedback.

The diagram in **Figure *14*** presents the responses to Question 2.2, which evaluates how clear and intuitive users find the steps for uploading Hazard, Exposure and Vulnerability data, including the clarity of the validation feedback provided. The results show that all respondents rated the process as either "Very clear and easy" (55.5%) and "Clear" (44.5%), indicating a generally positive perception of the data-upload workflow.

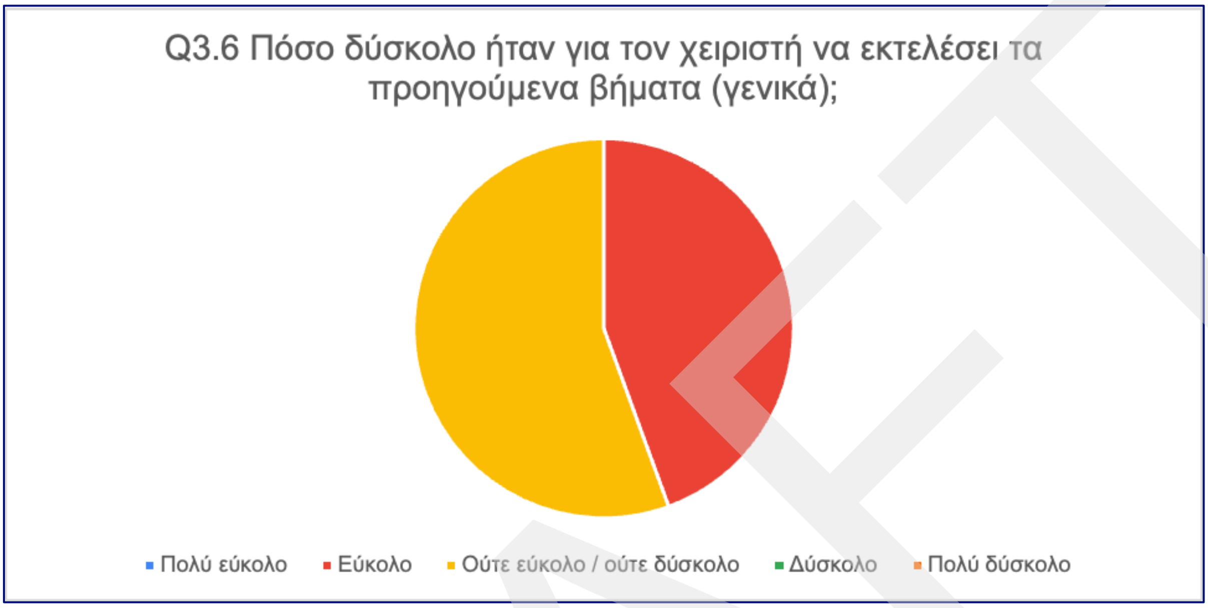


Figure 15. Answers to the question of the user experience on the use of the DSS

The diagram in **Figure *15*** summarizes responses to Question 3.6, which asks how difficult it was for the operator to perform the previous steps, in general. The pie chart shows that respondents mainly selected "Easy" (44.5%) and "Neither easy nor difficult" (55.5%), while there were no responses in the "Very easy," "Difficult," or "Very difficult" categories. This shows that users did not perceive the workflow as particularly burdensome overall.

Observer Findings

The questionnaire gathers feedback from 10 respondents, who are representatives from all tables, regarding the Decision Support System (DSS) tool. Participants rated the tool using a 1-5 Likert scale across five sections: Q1 (sign-in and start), Q2 (Risk Impact Assessment including data upload), Q3 (RAF/Resilience Assessment Framework), Q4 (RAF outputs and PDF), and Q5 (Map Viewer). Overall, the ratings tend to lean positive, with many scores of 3 (acceptable/neutral), 4, and 5 (good/excellent), along with occasional 1s and 2s (poor/difficult) in the initial steps. This indicates strong usability of the core functions, though there is potential for enhancing the onboarding process.

Strengths

- All users rated data upload (Q2.2 Hazard/Exposure/Vulnerability) as very clear or clear, with intuitive validation feedback.
- RAF steps (Q3) and Map Viewer (Q5) received mostly easy or neutral ratings, e.g., Q3.6 was rated as easy or neither by everyone.

- Sign-up/start (Q1.1) often took just 5 seconds; R.I.A. Manager (Q2.3) and outputs (Q4) consistently scored 3+.

Weaknesses:

- Several early Q1 steps like Q1.2-Q1.5 received low ratings (1-2), with 7 instances of a rating of 1 across respondents, indicating issues after sign-in before the main workflow.
- Most scores were neutral (3s) in summaries (Q1.6) and some RAF/Map tasks, showing acceptable but not excellent navigation and jumps (Q3.1).
- While there are no outright failures, variability in scores (e.g., Q2.1 with ratings 1, 3, and 5) suggests inconsistent experiences possibly linked to user familiarity.

Feedback from participants

The participants gave positive feedback on the use of the DSS for the wildfire risk assessment for the case of Rhodes Island. The key feedback outcome was:

- Ease to use and to navigate.
- No scientific expertise is needed by the user, in case the data exist.
- The report is easy to understand, despite the language barrier by some CoP members.

In addition to the CoP member feedback, they requested the addition of more hazards that can be assessed by the DSS. Emphasis must be given on the request by the public authorities (Civil Protection) of the continued support, improvement, and extension of the DSS (to more hazards) as a tool to assist in the climate adaptation of the island and a mean to reduce climate related risks.

3.5.4 Summary of trial findings

The trial activities conducted in the AMB, SLZ, and SAR locations aimed to evaluate the usability, relevance, and potential operational value of the ICARIA Decision Support System in diverse geographical, institutional, and hazard contexts. Across all three trials, stakeholders from public administrations, infrastructure operators, civil protection authorities, and research institutions interacted with the DSS through guided workflows, scenario-based exercises, and structured feedback mechanisms, including surveys, observer-based assessments, and plenary discussions. The detailed results are presented in Sections XX-XX (3.5.1-3.5.3?) for each of the trials. This following text draws on findings from across the trials to identify common strengths, limitations, and lessons learned, supporting system improvement and informing future initiatives.

Perceived Strengths

Feedback from all three trials indicates **the high perceived relevance and potential usefulness of the ICARIA DSS.** Participants across all three locations recognized the value of a tool that integrates climate projections, risk and impact assessments, resilience assessments, and scenario comparison within a single platform. Even when direct, frequent operational use was not yet considered likely, stakeholders acknowledged the **DSS as a promising support tool for strategic planning, policy design, and climate adaptation decision-making.**

Across all trials, the **conceptual structure of the DSS,** organized around projects, scenarios, hazard and risk assessments, and adaptation measures, was generally well understood and aligned with user expectations. **Core analytical functionalities**, i.e., scenario comparison, visualization of climate projections, and resilience assessment outputs, were repeatedly highlighted as among the most engaging and valuable features. **The ability to compare alternative hazard or adaptation scenarios** was regarded as one of the strongest assets of the platform, supporting informed discussion and exploration of future pathways and scenarios.

Navigation and general workflow were also perceived positively once users were sufficiently oriented. In AMB and SAR, many participants found the platform intuitive and easy to explore with minimal guidance, while in SLZ users reported that navigation became manageable after an initial familiarization phase. This indicates that the overall design logic of the DSS is sound, though it is important to have an initial onboarding.

Finally, all trials demonstrated a **strong interest in extending the DSS** beyond the specific trial contexts. Participants widely agreed that the methodologies and resilience assessment functionalities are transferable to other regions, assets, and hazard contexts, provided that suitable data are available.

Perceived shortcomings and Limitations

Despite the positive reception, several common challenges emerged consistently across the trials. The most prominent relates to **data requirements and preparation**: while the technical process of uploading hazard, exposure, and vulnerability data was generally clear, many users struggled to understand what type of data were needed, how to prepare them, and the level of expertise required. Closely related is the **need for expert knowledge during risk and impact assessments and resilience questionnaires,** which was frequently cited as a key limitation of the current prototype. Other recurring issues included **clarity and transparency of complex elements**, such as RAF and RAT charts, map viewer functionalities, and **limited system feedback** during long-running processes, which sometimes caused uncertainty or disorientation.

While overarching lessons were largely consistent across trials, some **context-specific differences were observed,** including differing stakeholder priorities, varying interests in resilience assessment functionalities, and the need to adapt concepts and indicators to specific territorial or governance settings, such as rural or island contexts.

Participants also highlighted the importance of addressing complex and cascading risk mechanisms that are not yet fully captured by the DSS. Overall, these findings underscore the **need for flexibility, broader hazard coverage, and continued system development** to support sustained operational use, long-term adaptation, and effective risk reduction across diverse contexts.

Generally, the **DSS concept was positively received**, but the stakeholders highlighted that it would benefit from **further refinement before broader operational deployment**, particularly regarding hazard coverage, modelling depth, and data integration. This was to be expected due to the targeted lower TRL level of the project.

Recommendations

Based on these findings, we identified **potential next/future steps,** which could be improved or highlighted for the planned mini-trials or in follow-up activities (e.g., post-project). They include the development of **clear, user-friendly guidance for data preparation, improved onboarding and system feedback, and the simplification of complex visualizations and multi-step workflows.** Further improvements would **be expanding hazard and risk modelling, increasing transparency of inputs and assumptions, and adapting the DSS to different territorial and governance contexts,** such as rural areas and island environments, to support broader and sustained operational use.

3.6 Methodology recommendations

As already indicated in sections 3.1 and 3.2 of this document, the TGM has been designed for use in the crisis management context. This section **summarizes the lessons learnt in applying the TGM in ICARIA trials and formulates the recommendations** for other projects and stakeholders in the Climate Action domain.

3.6.1 R01: Reword and interpret the relevant naming conventions.

Every domain has its own naming conventions. While most of the scientists working in ICARIA were already familiar with both the terminology used in Crisis management context and the one used in Climate Action context, this isn't the case for other stakeholders involved in the project, nor for the project-external CoP members. Such terms as the “Crisis Management organizations” “common operational picture”, “exercises”, need to be translated into the language the project participants and domain stakeholders are familiar with to avoid misunderstandings. For example, the Table 5 in D4.1 (Havlik et al, 2024) explicitly translates “Trial Owner” into “Problem Owner”, “Practitioner Coordinator” into “Case Study Facilitator”, “Crisis Management Practitioners" into “Community of Practice” and “Extended Trial Team” into “Core Team & CoP members”

3.6.2 R02: Adjust the trial participants number and event duration

Trials organized in DRIVER+ and subsequent Crisis Management projects such as TeamAware or STAMINA tend to be either large stand-alone events or sub events embedded into massive multi day exercises. This isn't the case in ICARIA: our stakeholders aren't used to large multi-day exercises, and we had to adjust the trial event duration accordingly. In addition, we also realized that there is **no sense in involving a massive amount of people in the trial**. Due to the nature of ICARIA solutions, we didn't need any "boot on ground" and the number of stakeholders that will ever actively use the tools is limited.

We have observed a similar pattern in other Climate Action projects, such as ClimEmpower and KNOWING, and therefore believe that the **half-day trial events are likely to be better suited for many (most? all?) trials in the Climate Action domain, rather than 1.5-2-day events that are recommended by TGM** and common in the crisis management domain**.**

3.6.3 R03: Keep the number of solutions / features validated in a trial manageable

Moreover, **we recommend limiting the number of solutions or solution features that are validated through hands-on evaluation by trial event participants in the final trial event as low as possible** and to concentrate on key features rather than trying to do a complete tour of all the solution features. In this way, it is possible to **ensure that the key features of solutions are actively used by participants, rather than trying to rush through all the features developed in the project**, as proposed in D4.1, due to the lack of time. This can be done in several ways, depending on the context:

- **Split validation in multiple smaller trials** rather than one where all the solutions / features are trialed. This is a simple solution, but it might add too much overhead for trial preparation.
- **Organize parallel sessions** where different stakeholders validate different solutions / features simultaneously during the trial event, rather than validating them one after another. This is best suited for trials where each solution / feature addresses different gaps and different stakeholders and for trials where solutions are closely interconnected with input-output relations. It also requires a larger number of people participating in a trial event, which can be a logistic challenge.
- Finally, the solution adopted in ICARIA, where **only the central solution is validated in the main trial event, while the sub-solutions are already validated prior to the trial event** is a good compromise that may not be fully aligned with the TGM but excels in minimizing the trial planning and development overhead, while keeping the trial event manageable and assuring that all solutions are adequately tested by relevant stakeholders.

3.6.4 R04: Organize a chain of events during the trial execution, rather than a single trial event

Trials are often overloaded, both in terms of the organization and in terms of the expectations. In fact, the first trial Organized by the DRIVER project was criticized by the reviewers as a failure because they judged it as a demonstration and wondered why various failures in tools and processes were discovered during the trial.

The decision to Organize a chain of events (trial-> mini trial ->demonstrator) has allowed us to declutter the trial organization and better manage the expectations: trials are meant to discover issues and therefore we kept the audience limited to participants with high interest in the project who are likely to actively use the ICARIA solutions (or similar). Mini trials can involve participants from follower regions and those that are only interested in results, not in ICARIA software and modelling tools. And finally, the demonstrator can then be used to present ICARIA results in the best light to the wider public.

Even so, we ended up adding additional event(s) specifically for testing the RAF/RAT functionality, which wasn't initially planned. Generally speaking, organizing a series of simple events with clear goals and short duration is preferable to organizing an all-encompassing trial. This approach keeps the stakeholders involved in the project without overwhelming them and also minimizes the risk of failure.

3.6.5 R05: Use ICARIA Research Questions as a starting point for developing own trials

Research questions connect different aspects of the trial: they address specific trial gaps, need to be answerable in an objective way within the trial, and need to be understood and approved by all trial stakeholders. Good research questions are formulated in a simple and easy-to-understand way and have a clear relation to trial gaps and objectives.

Research questions defined in ICARIA are sufficiently generic to be applied to many different trials and types of solutions in the Climate Action space. They cover several key categories of interest to Climate Action projects and stakeholders, and they are already structured in a way that suggest how the answers can be collected - i.e., as questions with simple (yes/no, good/bad/evil, 0-5 likert scale, etc.) answers, short texts (e.g., lists of suggestions), long texts (full responses / recommendations) or even require more complex deliberations (mainly the scientific validation). We therefore recommend research questions listed in Table 22: ICARIA research questions for the trials as a foundation for designing future trials in the Climate Action space.

3.6.6 R06: Use appropriate data collection methods to resolve the Research Questions

ICARIA Research questions cannot be resolved by a single data collection method. A combination of different methods that was recommended to trial owners for collecting the relevant data and eventually resolving the research questions is indicated in Figure 2 in section 3.4.3 and summarized in Table 11 below.

Table 11. Mapping of ICARIA research questions to data collection methods. "+" = primary recommendation, "*" = secondary recommendation, "-" = not recommended

RQ No.	Research Question	Data collection method				
		Team	Observers	Interactive	Survey	Interview
RQ-Sci1	How plausible/reliable are ICARIA data/modelling results?	+	-	*	-	*
RQ-Sci2	How easy/difficult/expensive would it be to apply the ICARIA solutions in new regions?	+	-	-	-	*
RQ-Sci3	Which data/modelling aspects of ICARIA solutions need to be further developed/improved?	*	*	+	+	+
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?	*	-	+	+	+
RQ-Ex1	How easy or difficult is it to use the solutions?	-	+	-	-	-
RQ-Ex2	How easy or difficult is it to understand the results/recommendations offered by the solutions?	-	+	*	*	-
RQ-Ex3	What needs to be done to improve the user experience / usability of the solutions?	-	+	*	*	-
RQ-Acc1	How useful is ICARIA methodology for the Regional Authorities and other stakeholders?	-	-	+	+	*
RQ-Acc2	How useful are ICARIA solutions for the Regional Authorities and other stakeholders?	-	-	+	+	+
RQ-Acc3	Do potential users want to use this type of solutions in their work?	-	-	+	*	*
RQ-Acc4	Which improvements / additional features would make the ICARIA methodology and/or solution(s) significantly more attractive for potential users?	-	-	+	+	+
RQ-Soc1	How much socioeconomic impact (including gender and ethics issues) do trial participants anticipate from ICARIA methodology and solutions?	-	-	+	+	*
RQ-Soc2	What kind of socioeconomic impacts (including gender and ethics issues) do trial participants anticipate from use of ICARIA methodology and solutions?	-	-	+	+	*

In short, we our recommendations are:

1. **Questions related to plausibility and transferability Science and technology (Sci1, Sci2) need to be mainly resolved by scientists and developers working in the project**. Ideally, the scientific partners should design tests where the quality of data/modelling results can be objectively evaluated and report the findings in a transparent way that allows independent falsification of the results. Alternatively, the quality of the data and modelling results could also be validated by external experts, e.g., through a peer review or relevant scientific publications.
2. **Questions related to future extensions and to the level solutions that go beyond regional state of the art (Sci3, Sci4)** can be resolved by trial participants, either in **interactive voting** during the trial event, through **dedicated survey** and/or **interviews** with a small number of key stakeholders.
3. **Questions related to user experience (UX) are best answered by observers**. For this data collection method, two things must be prepared in advance: (1) a **detailed training/tutorial script** that is followed by (part of the) trial participants and (2) **a structured questionnaire** that is aligned with this script, mapped to research questions and used by dedicated observers to report their observations during the trial event.
4. **Acceptance questions (Acc)** are of high importance for exploitation planning and can be assessed from two points of view: **acceptance by the CoP members / trial participants** and **acceptance by their managers** and decision makers that can make investment decisions. With this in mind, research questions RQ1 to RQ4 should be resolved both through interactive activities or surveys with trial participants and through interviews with their managers / decision makers. In ICARIA, these questions were only partially resolved in trial and will be **further elaborated in mini trials**.
5. Finally, the **questions related to socioeconomic impacts (Soc)** should be primarily addressed by trial participants. In our experience, this is a challenging task for them—too abstract and removed from their daily work. We therefore recommend assessing these aspects through **dedicated group thinking exercises** rather than relying solely on interactive or full surveys. In ICARIA, this will be **implemented in the context of upcoming mini-trials**. Additionally, the scientific project team should prepare a list of potential impacts for stakeholders to assess, complementing the insights gathered when trial participants first articulate their own opinions.

3.6.7 R07: Think about features, not products

As indicated in deliverable D4.1 and section 3.4 of this report, it is difficult to align the solution election process that is inherent to TGM with the reality of research projects, where solutions need to be co-designed and developed in parallel with the trial.

In retrospect, we believe that the way we resolved this conundrum in ICARIA is suboptimal. In essence, we believe that solution description in this type of research projects should concentrate on the **features and processes stakeholders need and not on individual software.**

This is in line with the spirit of the TGM, which defines solutions as in **socio-technical innovations that are selected and assessed in Trials**. Solutions can be software, hardware, workflows, training, procedures, or combinations thereof, as long as they contribute to addressing a crisis management need or gap. In this context a **specific feature or workflow the project intends to implement, because stakeholders need it for bridging some operative gap is a "solution".**

Concentrating on well-defined requirements on features and workflows stakeholders need, rather than on specific features of the software (hardware, other) that hasn't even been implemented yet would **allow us to focus on what matters and what is known at a trial design phase and help in designing the trials accordingly**. This resembles the underlying software engineering paradigm of "Test Driven Development", where automated unit tests are written before the functional code, thus providing both a way to express expectations and to design a validation upfront rather than once the product is already developed.

To the best of our knowledge, this approach to TGM design has not been tried before, but we are currently implementing it in the context of ClimEmpower trials.

4 ICARIA risk assessment

4.1 ICARIA trial solutions

Chapter 4 is organized as follows: Section 4.1 is an overview of the ICARIA risk assessment framework, Section 4.2 presents in detail the development of the single and multi-hazard model for each CS Trial activities, and Section 4.3 indicates the effects, in terms of risk increase or reduction, of climate and adaptation scenarios considered in each assessment. The hazard models presented in this chapter correspond to activities defined in the Trial architecture of each CS as they are

The ICARIA project has developed a holistic framework for natural hazard risk assessment that responds to the growing complexity of climate-related disasters (Leone et al., 2025). Traditional single-hazard approaches, where floods, droughts, wildfires, or heatwaves are studied independently, have proved inadequate for assessing the risk of multi-hazard events (either consecutive or coincident) (Russo et al., 2023). Furthermore, classic methodologies often overlook the potential cascading effects that extreme weather events can cause on interdependent services and infrastructures. This aspect becomes especially critical in urban areas. In this sense, the ICARIA framework provides a harmonized methodology capable of capturing the dynamics of multi-hazard risk and its consequences for critical assets, infrastructures, and communities. Ultimately, it contributes to the overall objective of "contributing to a better understanding of climatic hazards and improving the resilience of critical infrastructure".

At the conceptual level, the framework builds upon the consolidated risk assessment metrics, where risk is defined as the combination of Hazard (H), Exposure (E) and Vulnerability (V). Based on this, it evolves this into a more comprehensive assessment that takes into account other relevant aspects to assess risk and resilience. These are defined as the "elementary bricks.": Hazard (H), Exposure (E), Vulnerability (V), Dynamic Vulnerability (DV), Damage (D), and Resilience capacities (coping, adaptive, and transformative) (see **Figure *16***). This allows accounting for both physical processes and socio-technical dimensions, while also integrating the time and space variables and the modifying role of human behavior. In practice, this means the framework can describe how risk factors evolve before, during, and after an event, and how previous shocks and preparedness measures modify the vulnerability of risk receptors and the resulting impact of future events. This approach is aligned with the risk-based guidelines for risk assessment defined in the reports AR5 and AR6 of the Intergovernmental Panel on Climate Change (IPCC), as well as the Sendai Framework for Disaster Risk Reduction (IPCC, 2023a; UNDRR, 2015).

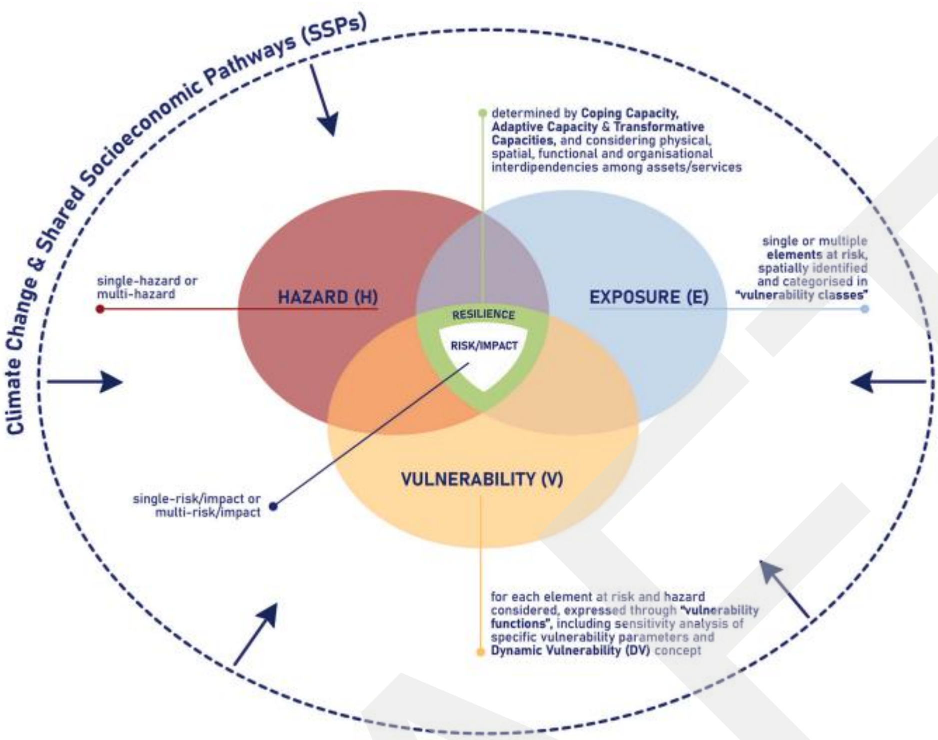


Figure 16. Conceptual representation of the ICARIA Framework (Leone et al., 2025)

Importantly, the methodology is conceived as a tool to develop risk assessment for particular risk receptors such as critical infrastructures (e.g., water or electricity distribution networks), assets and services (e.g., transportation networks), or other relevant receptors such as pedestrians exposed to floods or natural areas. For this reason, the application of the ICARIA framework requires a previous characterization of the "elementary bricks" elements for the specific hazard and risk receptors that need to be assessed. The methodological background to apply the framework in the three ICARIA case studies is collected in (De La Cruz–Coronas et al., 2023; Guerrero-Hidalga et al., 2024).

One of the main innovations of the ICARIA framework is its capacity to simulate complex event chains or cascading events by representing the multi-hazard interactions through "event trees". These schemes can be understood as a "storyline" to, first, identify all the interactions established during the event and, second, define the most adequate strategy to assess the resulting risk. In parallel, the inclusion of dynamic vulnerability functions ensures that the condition of exposed elements is not treated as static but as evolving in case it is relevant for the assessed risk receptor. **Figure 17** depicts an example of an "event tree" for the Metropolitan Area of Barcelona (AMB) case study.

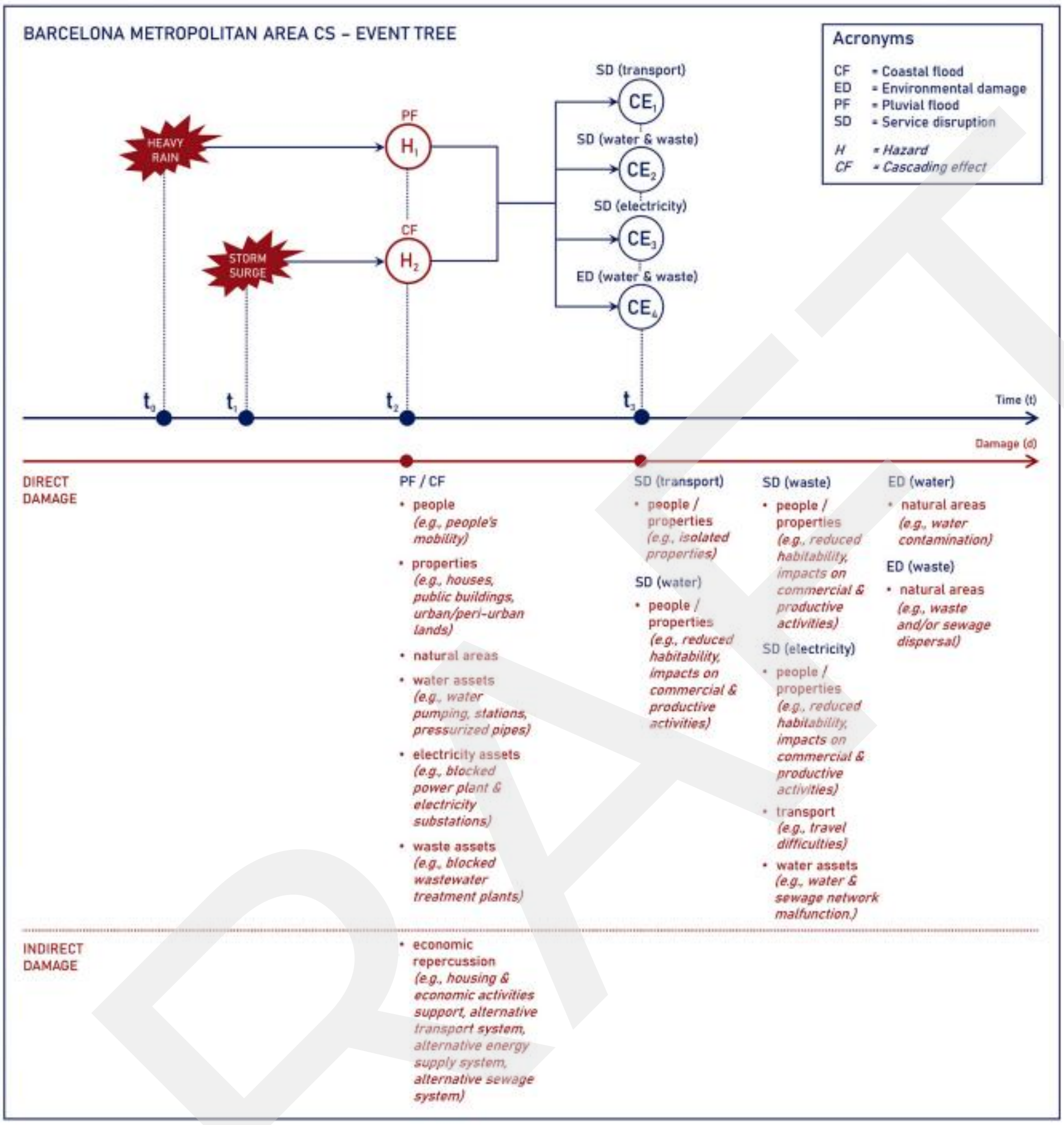


Figure 17. Representation of a plausible event tree occurring in the Barcelona Metropolitan Area case study (Leone et al., 2025)

The framework also provides a robust basis for testing adaptation scenarios. By modelling how different measures alter hazards, exposures or vulnerabilities, it is possible to assess the effectiveness of interventions under future climate conditions. For example, changes in land use planning, infrastructure reinforcement, or early warning systems can be introduced into the modelling chain to evaluate their impact on risk reduction. These outcomes are then post-processed using cost–benefit analysis and multi-criteria analysis tools, ensuring that decision-makers can compare alternatives not only in terms of damage reduction, but also with respect to social, environmental and economic co-benefits.

To ensure its applicability, the framework is designed as a decision-support tool for authorities, infrastructure operators, urban planners and communities. By linking hazard projections with exposure, vulnerability, and resilience metrics, it translates scientific modelling into policy-relevant information. It highlights priorities for intervention, identifies cross-sectoral vulnerabilities, and underlines where measures can generate systemic benefits. It also helps to manage uncertainty by harmonizing data and providing a common structure for comparing scenarios across hazards and regions. A complete explanation of the ICARIA Framework is presented in ICARIA Deliverable 1.1 (Truchi, et al., 2023).

4.2 Hazard models description

4.2.1 Barcelona Metropolitan Area CS hazard models

Figure 18 shows the architecture of the AMB case study in the ICARIA trial. The climatic drivers considered are extreme precipitation and sea level, which can cause pluvial floods and storm surge conditions impacting critical assets in the region. From a multi-hazard perspective, the impacts of the joint occurrence of coincident extreme precipitation and storm surges are part of the case study work. The risk receptors of interest are people, populations, natural areas (beaches) and strategic services like transport, water sector, electricity and waste. Consequences of cascading effects are specifically assessed for the electricity sector.

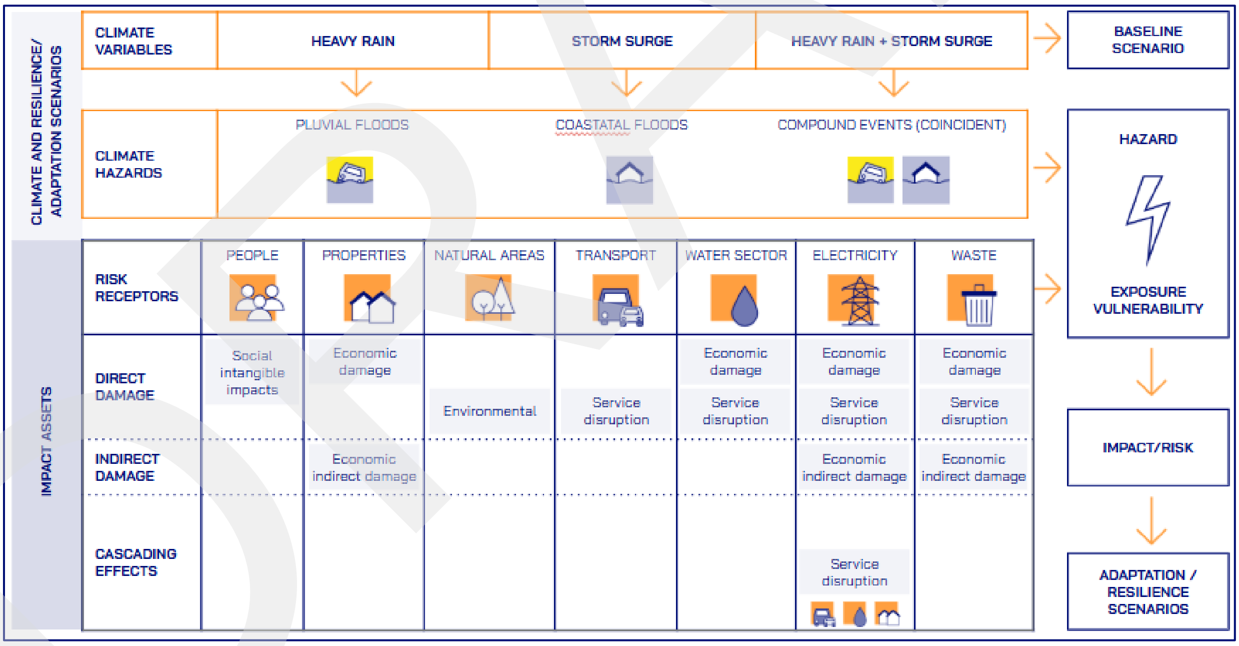


Figure 18. AMB CS trial architecture

4.2.1.1. Pluvial flood single hazard model

Model context

The Metropolitan Area of Barcelona (AMB) is a densely urbanized region of 636 km² comprising 36 municipalities and 3.3 million inhabitants. Its geography combines steep peri-urban terrain with highly populated riverine and coastal plains. This configuration creates adverse hydrological responses, favoring rapid runoff generation and propagation during intense rainfall. The region has a Mediterranean climate characterized by irregular and torrential precipitation, with a significant share of annual rainfall during short, high-intensity convective storms (De La Cruz–Coronas et al., 2023).

Drainage infrastructure in the AMB is complex. Each municipality owns a sewer system, which is operated by multiple actors, while the metropolitan authority manages a supra-municipal interceptor network that connects local systems to seven wastewater treatment plants. This complicates the development of a harmonized regional hydrodynamic model.

Given the complexity of the AMB CS, a consistent assessment requires the creation of a metropolitan-scale, coupled 1D/2D hydrodynamic model following the precedent of past EU projects like RESCCUE (Russo et al., 2020), BINGO (Eduardo Martínez-Gomariz et al., 2019) and CORFU (Russo et al., 2015). This modelling tool includes heterogeneous datasets, reflects the interaction between surface runoff and the sewer network, and incorporates relevant boundary conditions.

Model scope and objective

The objectives of this model are as follows:

I. Based on a previous calibration and validation of the model, provide flood maps detailing water depth and velocities on the surface for a set of rain events (historic and synthetic) with different return periods and climate change scenarios (including adaptation).
II. Allow the incorporation of riverine and sea boundary conditions to allow multi-hazard assessments.

Main model features

The metropolitan hydrodynamic model is developed using ICM Ultimate v2026.2 and follows a coupled 1D/2D scheme. Its main features and innovations are as follows:

- Fully coupled 1D/2D hydrodynamic covering the whole AMB (little precedents of such an extensive and detailed model are reported in literature).
- The totality of the 36 municipal networks and the metropolitan interceptor system is included in the model.
- The model conceptualization follows a hybrid approach, meaning that the model combines a detailed 2D mesh for open surfaces with sub-catchments representing individual buildings. Runoff generated on roofs is routed directly into the sewer network, while runoff produced on streets and open areas is computed in the 2D domain.

- Water exchange between the 1D and 2D domains is based on the hydraulics of inlets assigned to each node and through outfalls.

The following table summarizes the model elements.

Table 12. Summary of elements in the AMB coupled 1D/2D flood model

Model elements	Number
Nodes	174,900
Storage tanks	309
Inlets	396,200
Pipes	180,830
Pipe length (Km)	4,950
Pumps	104
Wiers	1,200
Outfalls	1,300
Mesh elements	6,800,000

Model Setup

Model setup consists of four major aspects: (i) surface domain discretization, (ii) hydraulic and hydrologic parameterization, (iii) sewer network assembly, and (iv) definition of surface–network connections.

I. Surface domain discretization

The 2D domain of the model is based on a 2 × 2 m digital terrain model of the AMB. This dataset is complemented with land-use maps, hydrological classifications, and cadastral building data, ensuring a consistent representation of urban, peri-urban, and natural areas. To balance spatial accuracy with computational demands, different meshing densities are considered: a fine unstructured triangular mesh with cells 25 to 100 m² is used in urban areas although the resolution is much more detailed in case of complex topographies such as narrow streets or the need to represent complex urban elements such as fountains, roundabouts, etc., while peri-urban areas are discretized with larger elements (from 500 to 1000 m²). Key low-lying regions, such as the Llobregat delta, are included within the high-resolution domain for better resolution. Following the hybrid model setup, all building footprints are considered as voids in the terrain mesh, allowing surface runoff to move realistically along streets and open paths. Also, each building is modelled as an individual sub-catchment, collecting rooftop rainfall and routing it directly to the sewer network through the nearest node within 100 m. This dual representation preserves both the physical obstruction caused by structures and their hydrological response to rain. The final surface domain comprises approximately 6.8 million mesh elements, providing the resolution required for metropolitan-scale pluvial flood simulation.

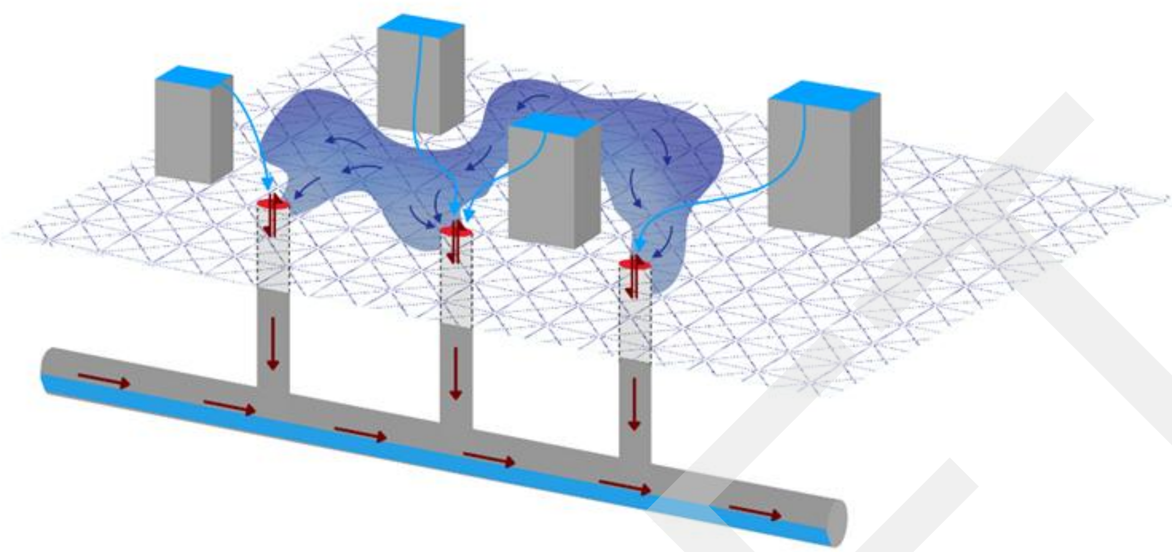


Figure 19. Conceptual model of a coupled 1D/2D model with a hybrid structure

II. Hydraulic and Hydrologic Parameterization

The model assigns rainfall losses and infiltration processes according to an 11-class hydrological scheme combining soil groups and land-cover categories. Permeable areas use Horton infiltration curves, with initial rates and decay constants values based on regional hydrological references. Impervious surfaces are assigned fixed initial losses and no infiltration, reflecting local drainage behavior. Manning roughness values are specified for each land-use class accordingly (see **Table *13***).

Table 13. Hydrologic parameters of the model

Land use	Hydrologic classification	Infiltration type	f_0 (mm/h)	f_k (mm/h)	K (1/h)	f_r (1/h)	Initial loss (mm)	Manning roughness
Forest	A	Horton	127	11.43	15.5	0.036	n.a.	0.2
Forest	B	Horton	76	7.6	15.5	0.036	n.a.	0.2
Forest	C	Horton	42	3.8	15.5	0.036	n.a.	0.2
Forest	D	Horton	25	1.27	15.5	0.036	n.a.	0.2
Agriculture	A	Horton	254	11.43	15.5	0.036	n.a.	0.2
Agriculture	B	Horton	152	7.6	15.5	0.036	n.a.	0.2
Agriculture	C	Horton	85	3.8	15.5	0.036	n.a.	0.2
Agriculture	D	Horton	50	1.27	15.5	0.036	n.a.	0.2
Green urban areas	n.a.	Horton	76	13	4.14	0.036	n.a.	0.2
Impervious areas	n.a.	Fixed loss	n.a.	n.a.	n.a.	n.a.	3.0	0.018
Roads	n.a.	Fixed loss	n.a.	n.a.	n.a.	n.a.	3.0	0.018

III. Sewer Network Assembly

The 1D sewer network integrates all 36 municipal drainage systems and the supra-municipal interceptor network, including nodes, pipes, manholes, surface inlets, storage structures, weirs, pumping stations, and other singular infrastructures of all drainage systems. This information was provided by the municipalities and operators of all local sewers, meaning a large number of data owners. Thus, its integration involved a comprehensive standardization process regarding geometry, metadata, hydraulic attributes, and coordinate references. In fact, datasets were only obtained for 25 municipalities. Among those, data quality was heterogeneous, and some cases required additional work to adjust the existing information to make it valid for modelling. For the remaining 11, the model relied on Synthetic Sewer Networks (SSN) using a methodology developed and tailored for the AMB context. The SSN generation process involves several key steps. Initially, input data is pre-processed, including the hydraulic domain, DTM, street layout, building locations, water courses, and network element characteristics. The sewer network layout is then defined based on the street map, with manholes placed at junctions and regular intervals, considering similarity criteria among the different networks of the analyzed region. Outfalls are located at the lower end of the model domain. Next, network dimensioning is performed by assessing preferential water paths, assigning order numbers to streams and pipes, and determining pipe diameters and depths accordingly. Finally, a routine identifies and corrects potential errors in the generated SSN, ensuring consistency and accuracy in the final network. More information can be found in specific recent publications (De La Cruz–Coronas & Russo, 2025). **Figure *20*** reflects the mentioned data sources.

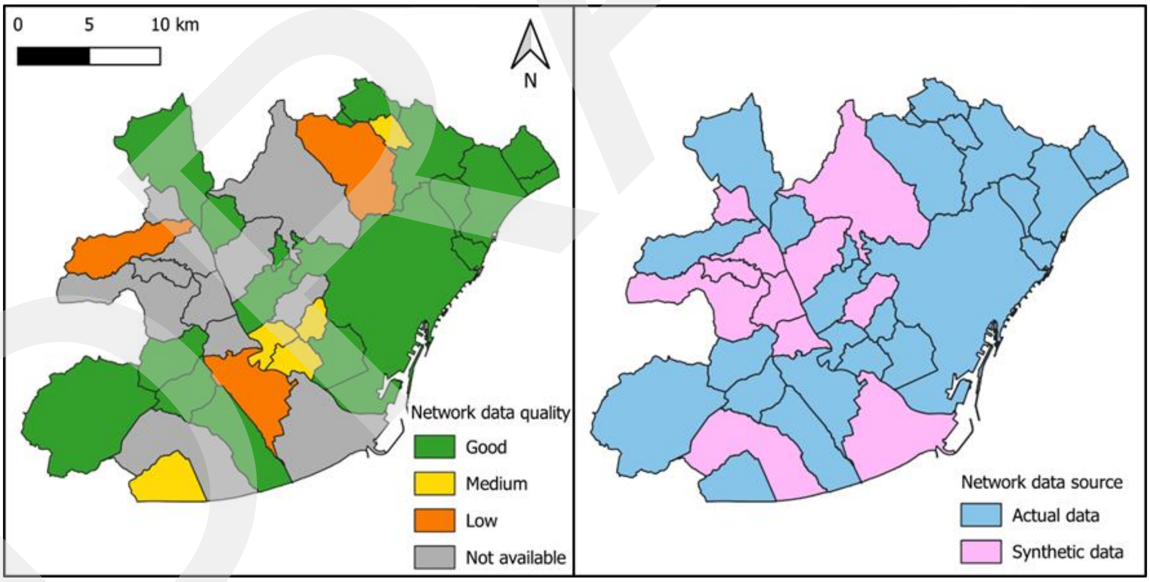


Figure 20. Drainage network data source (right) and quality of the information received (left)

IV. Definition of Surface–Network Connections

Surface–network interactions are represented through a detailed modelling of stormwater inlets. For each manhole it is assigned a specific number of inlets based on geospatial matching between inlet locations and manhole positions. The hydraulic performance of each inlet group is described using bidirectional head–discharge curves derived from experimental studies of grated inlets (Cosco et al., 2020; Russo et al., 2021). This approach allows the model to represent both limited capture during high-intensity storms and reverse flow when sewer surcharge occurs.

Outfalls are configured according to the receiving water body. Connections to the sea and the main rivers act as standard outfalls, removing water from the model, whereas outfalls to smaller streams are modelled as "2D outfalls" able to release flow onto the surface domain when water levels permit. This configuration allows the model to behave consistently during pluvial events, river-influenced conditions, and compound events with elevated sea levels.

Model calibration and validation

The model is calibrated and validated following the guidelines in Russo et al., 2015. However, sewer network monitoring in the AMB is heterogeneous. Only the cities of Barcelona and Badalona have a network of water level sensors valid for calibrating flood models. Furthermore, for both cases, access to data is limited. Therefore, the calibration and validation were based on four historic events that were selected for this process (see **Table *14***). For all, 5-minute precipitation intensity data for 12 rain events were available, together with 5-minute water level measurements from 18 limnimeters. All these data sources are limited to the city of Barcelona. As an example, **Figure *21*** presents the calibration and validation results for the limnimiter 100974.1.

Table 14. Data and events used for mode calibration and validation

Date	15/03/2011	07/06/2011	19/07/2011	30/07/2011
Cumulative rainfall (mm)	54.1	26.8	45.9	30.4
Max. 20' intensity (mm/h)	69.6	24.3	96.1	105.9
Max. 5' intensity (mm/h)	98.4	49.2	135.6	140.4
Event use	Calibration	Calibration	Calibration	Validation

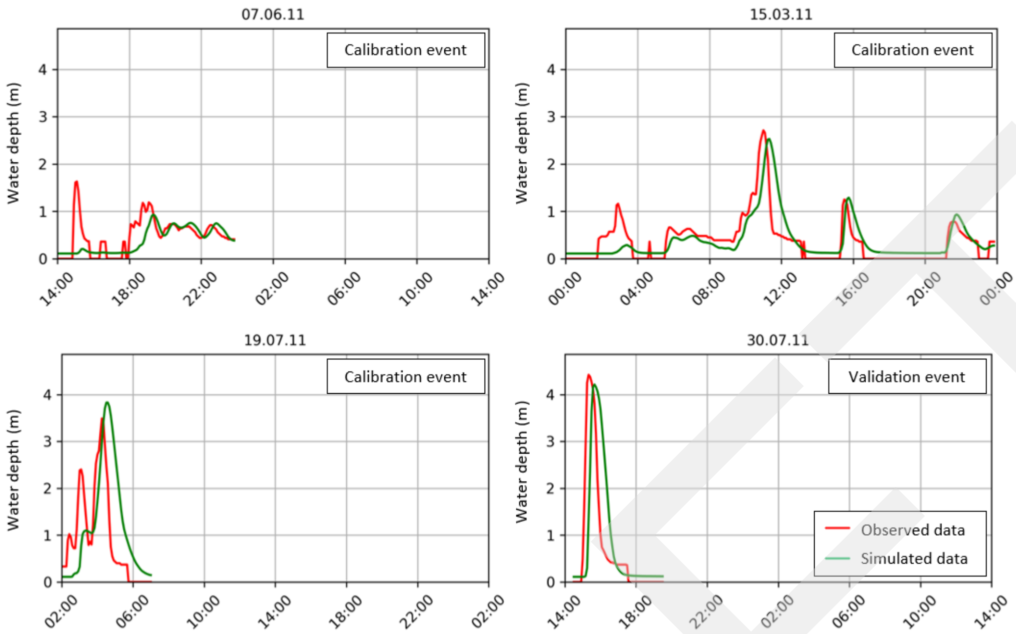


Figure 21. Calibration and validation results for the limnimiter 100974.1

The following figure shows an example of a flood map of the whole Metropolitan Area of Barcelona for a T10 historic rain event obtained from the ICM model presented in this section.

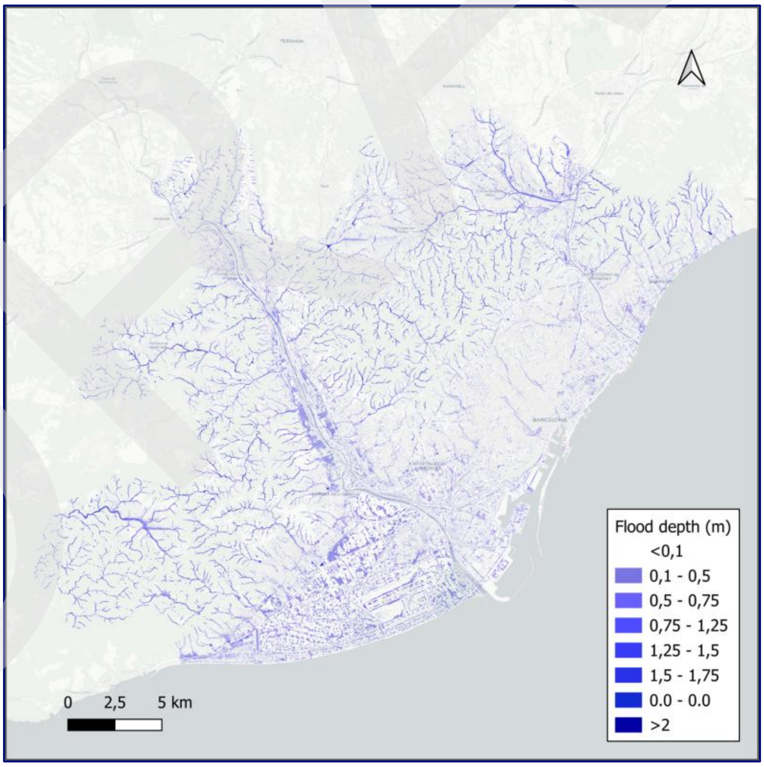


Figure 22. Flood map of the whole Metropolitan Area of Barcelona for a T10 historic rain event

4.2.1.2. Coastal flood single hazard model

Model context

The AMB is a coastal Mediterranean region with 42 km of seaside split between 8 municipalities (Badalona, Barcelona, Castelldefels, Gavà, Prat de Llobregat, Sant Adrià de Besòs, Tiana and Viladecans). Infrastructures and people in their low-lying coastal areas are heavily exposed to the effects of sea level rise and temporary extreme sea levels (ESL) associated with storm surges. The impacts of these sea-related hazards are multiple and have a relevant interaction with the sewer system overflows discharging into the sea (Chen et al., 2025).

Importantly, three different perspectives are considered in this study:

I. Firstly, a hydrostatic model developed for the AMB following the methodology in De La Cruz–Coronas et al., 2023, is used to assess the loss of coastal areas associated with the mean sea level rise.
II. Secondly, ELS values, representing the maximum wave height observed during storm surges, are used to assess the impact of waves on a coastal main sewer pipe (Insa, 2025).
III. Thirdly, the same ESL values are considered as sea level boundary conditions for the multi-hazard flood assessment in the AMB (see Section 4.2.1.3).

Model scope and objective

The objectives of this model are as follows:

I. Provide detailed flood maps of water depth in coastal areas for the mean sea level rise to assess the loss of coastal terrain
II. Assess the impact of transitory ESL on coastal infrastructure
III. Provide reference values for the multi-hazard flood model of the AMB

Main model features

The assessment is developed in QGIS, applying hydrostatic concepts considering three different approaches:

- Mapping of coastal flooding as a consequence of mean sea level rise based on a hydrostatic model (approach 1).
- Assessing the impact of ESL on a coastal sewer pipe. This implies assessing the propagation of waves on the coast on the AMB (approach 2).
- Determining the ESL at the shoreline of the AMB to define the boundary conditions for the multi-hazard flood model (approach 3).

Model Setup

The assessment considered in the first approach (coastal flood due to the mean sea level rise) involves the following steps.

I. Terrain and Coastal Domain Configuration

The model is based on a DTM of the coastal area with a 2 × 2 m resolution. For better representation of the land–sea interface, the DTM is complemented with building footprints, which are incorporated as raised, impermeable barriers, allowing flood extents to reflect the presence of built infrastructure while preserving the continuity of flow through streets and open areas. The DTM is modified with GIS processes to prevent unrealistic inland "pools" and to ensure that only zones hydraulically connected to the sea can be flooded by sea level conditions.

II. Mapping areas affected by the mean sea level rise

Flooding is estimated by comparing the mean sea-level rise of different climate change projections with the terrain elevation at each cell of the DTM. Areas whose elevation lies below the sea-level rise value and remain hydraulically connected to the coastline are classified as flooded. The resulting maps indicate the water depth in each affected cell of the DTM.

The assessments corresponding to approaches 2 (impact assessment on coastal sewer pipe) and 3 (multi-hazard boundary conditions) require additional steps.

III. ESL assessment

ESL values are determined based on maritime data representing sea level rise, maximum wave height and the influence of tides (REF 2.1). Based on the analysis of historic and climate projection data, ESL associated with different return periods of storm surges is determined.

IV. Wave height propagation

Assessing the impact of ESL on specific coastal assets requires refining the previous process with an assessment of the wave height propagation along the shoreline. The propagation calculation is based on the methodology proposed by Insa (2025). The ESL determined for each event is correlated with data from the closest SIMAR point (RE Puertos del Estado), a database indicating key aspects like the peak period and wave direction on the Spanish shore based on historic data. This information is introduced in a wave propagation model that generates estimated wave height impacting coastal assets (Insa, 2025).

4.2.1.3. Combined flood multi-hazard model

Model context

As presented in Deliverable 2.4 (Chen et al., 2025), urban coastal areas are exposed to multi-hazard events involving coincident extreme precipitation and storm surge, which can create a transitory extreme sea level condition. Their joint effect can lead to more severe flood conditions in low-lying coastal cities. The AMB CS is a clear example of an area that can be affected by this phenomenon, as it occurred during the Gloria Storm in 2020 (Amores et al., 2020).

According to literature, this kind of multi-hazard event is particularly critical for the sewer overflow devices discharging into the sea, where backflow can occur. ESL conditions can cause the intrusion of seawater into the drainage system through these elements and limit the drainage capacity of the network, while heavy rainfall affects the area. As a result, water accumulation and floods on the city's surface can become larger.

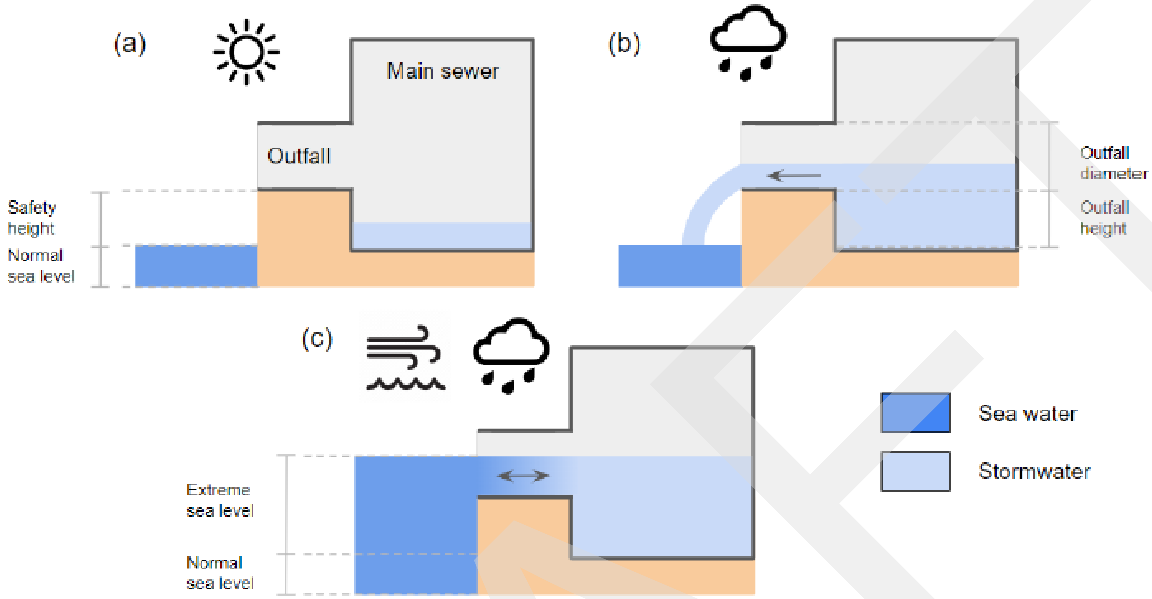


Figure 23. Scheme of a low-lying coastal area under different conditions: (a) dry weather conditions, (b) extreme precipitation; (c) coincident coincidence storm surge and extreme precipitation

In this study, the methodology followed to assess multi-hazard floods in the AMB CS is based on a loose coupling between the two single-hazard models presented in the previous sections. The ESL values resulting from the coastal flood assessment are defined as water level boundary conditions on the outfalls of the drainage network to simulate the mentioned backflow effect.

Model scope and objective

The objectives of this model are as follows:

I. Provide flood maps detailing water depth and velocities on the surface for a set of multi-hazard events representing different return periods and climate change scenarios.
II. Quantify the influence of elevated sea levels on pluvial flood hazard through backwater effects in the sewer network.

Main model features

The compound hazard interaction is implemented through a one-way coupling approach, consistent with the methodology outlined in Deliverable 2.3. In this configuration, storm surge does not directly generate surface inundation within the 2D domain. Instead, its effects are transmitted to the pluvial flood model exclusively through time-varying water level boundary conditions applied at sewer outfalls. The ESL time series corresponds to selected storm surge scenarios imposed at coastal outfalls of the sewer network. No 2D coastal boundaries or marine inundation domains are included in the model since the hydrostatic model used does not consider the hydrodynamics of coastal floods caused by storm surges. Thus, its results are not suitable to define boundary conditions in the 2D domain.

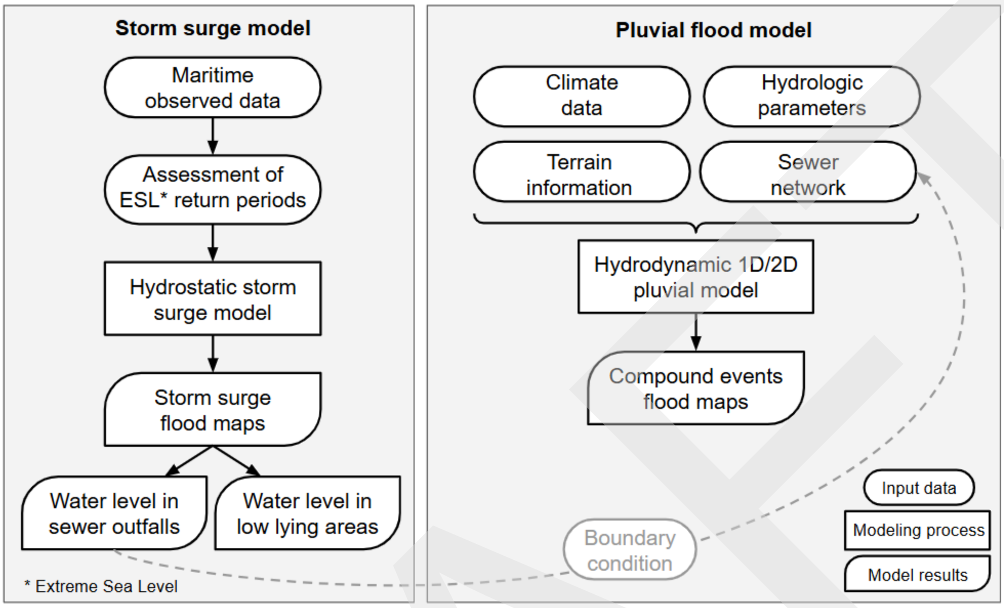


Figure 24. Coupling between the pluvial flood and storm surge single-hazard models

Model Setup

The setup of this multi-hazard adds just two additional steps to the ones of the single-hazard model for pluvial flood assessment.

I. Relevant outfalls identification

Identify the relevant sewer outfalls located in coastal areas potentially affected by storm surges. In total, 98 out of the 386 coastal outfalls in the model are considered relevant for ESL boundary conditions. The remaining 288 are located within port infrastructure that conditions the coastal dynamics. The hydrostatic model used to estimate ESL values is not valid for assessing abnormal sea levels in such areas.

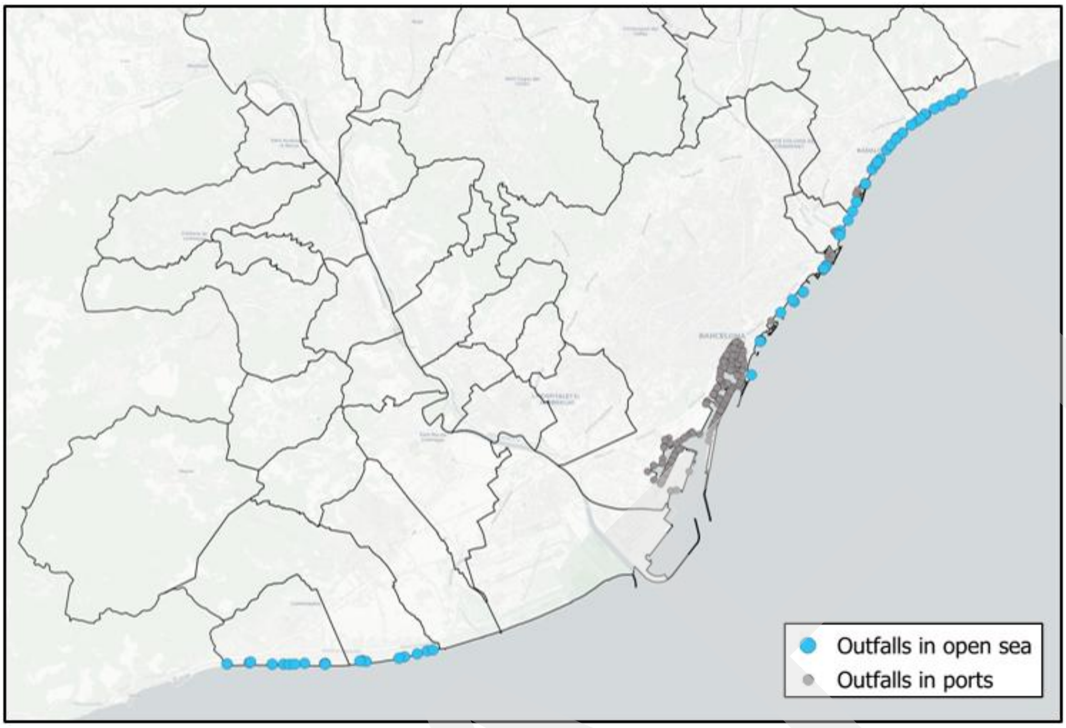


Figure 25. Outfalls in open sea (considered for ESL boundary conditions) and outfalls in ports (not considered for ESL boundary conditions)

II. Introduce the corresponding sea level boundary conditions

A time series representing the ESL conditions during the simulation is defined on each outfall outside of ports.

Model calibration and validation

No specific calibration is done for the multihazard models since, essentially, it is the already calibrated pluvial flood model with additional boundary conditions.

4.2.2 Salzburg Region CS hazard models

For the Salzburg region, pluvial flood and extreme winds were identified as main hazards to be treated within the trial, as is their compound effect. The risk receptors targeted for the different hazards were buildings and electricity infrastructure, as well as the road network for flooding. The impact on those risk receptors was computed with respect to economic damage and/or service disruption. In the following sections, the hazard models (pluvial flood, windstorms) are described in more detail.

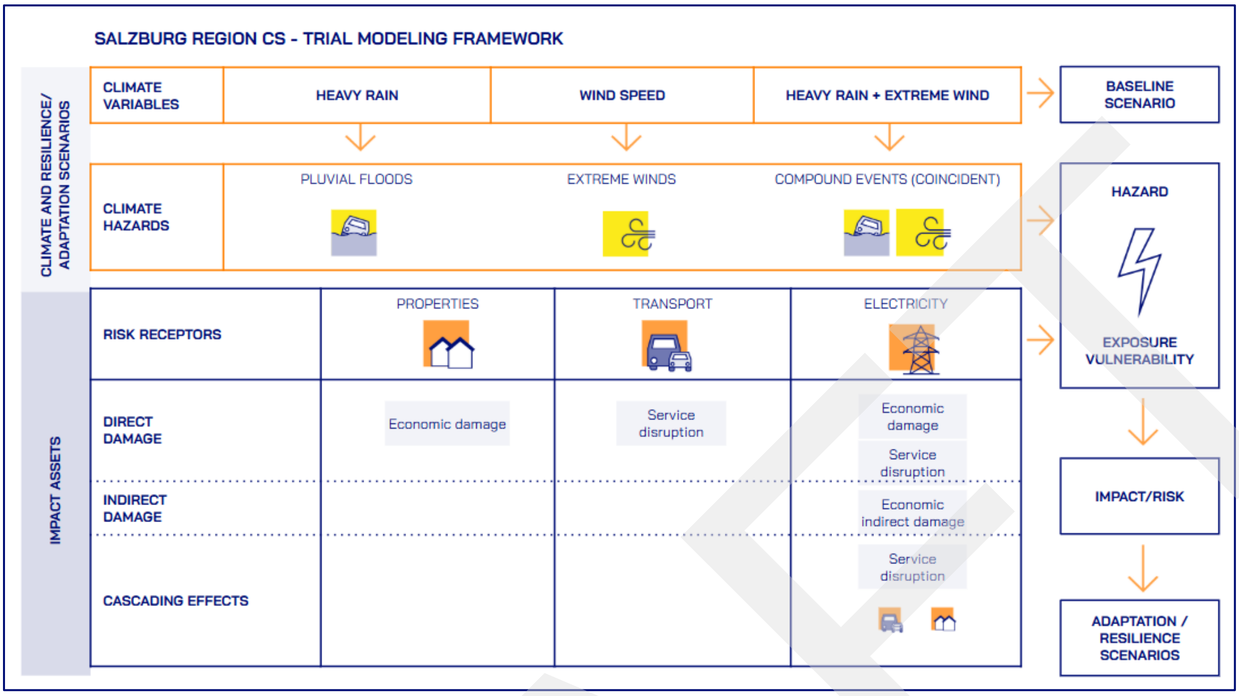


Figure 26. Salzburg Region CS architecture

4.2.1.1. Fluvial flood single hazard model

Model context

During the first ICARIA CoP meeting in Pinzgau, fluvial flood was identified as the main hazard for this region, focusing on the Pinzgau valley, located in the Austrian Alps of the federal state of Salzburg, as this area frequently hit with convective, heavy precipitation events. The established settlement's morphology in combination with the surrounding complex topography, make them vulnerable to damages caused by the heavy precipitation's pluvial floodings, already causing severe damage to the region's infrastructure. So, the Pinzgau valley's catchment was chosen as domain for ICARIA flooding hazard simulations within the SBG region. Pinzgau (District of Zell am See) covers about 2,641 km², making it the largest district in the state of Salzburg. It includes the upper Salzach and Saalach valleys and is divided into Upper, Middle, and Lower Pinzgau. The population is approximately 98,131 inhabitants (as of January 2024), resulting in a low population density of around 33 people per km². The main focus of ICARIA is on Mittersill, the biggest settlement of Upper Pinzgau with 5723 inhabitants (as of January 2025), as it is home to critical infrastructure such as a hospital and extremely affected and therefore constantly re-evaluating available adaptation measures and potential future ones.

Model scope and objective

The objectives of this model are as follows:

I. To provide flood maps detailing water depth on the surface for a set of rain events representing different return periods and climate change scenarios.
II. Testing the model for alpine regions applicability.

Main model features

For the achievement of SBG Flooding Hazards simulations, SFINCS (Super-Fast INundation of CoastS) model was used. It was developed by (Leijnse et al., 2021) with the initial intention of simulating compound flooding events caused, for example, by tropical cyclones. SFINCS is a hydrodynamic flood model designed for rapid simulation of inundation processes. Although originally developed for large-scale coastal flooding, SFINCS has become increasingly relevant for riverine flood modelling, particularly in contexts where high computational efficiency, large spatial extents, and limited input data availability are key constraints. The model operates on a sub-grid, raster-based formulation that solves a simplified version of the shallow water equations using a dynamic wave approximation. This approach captures key flow processes—water level gradients, inertia, storage, resistance—while avoiding the computational burden of full 2D shallow-water models.

For riverine flooding, SFINCS is well suited to simulate overbank flow, floodplain routing, embankment overtopping, and interactions between channels and floodplains. It represents rivers as hydraulic features embedded in the raster, allowing discharge hydrographs, water levels, or upstream boundary conditions to be imposed at channel inlets. Because SFINCS uses flexible spatial resolutions (from meters to hundreds of meters), it can represent complex floodplain topography, levees, dikes, and breaches while maintaining fast runtimes, enabling extensive scenario exploration and climate-impact assessments.

Friction is implemented using Manning's coefficients, and infiltration/runoff options are available to approximate hydrological processes influencing floodplain storage. Sub-grid parameterization allows narrow channels or embankments to be represented even if they fall below the model grid size. SFINCS can be coupled with rainfall-runoff models, river routing models, or climate scenarios to support probabilistic and long-term riverine flood risk analysis.

Model Setup

For model set-up and calibration, a pluvial flooding event from the 29.07 to the 01.08.2014 was selected. The precipitation intensity and pattern is taken from the INCA (Integrated Nowcasting through Comprehensive Analysis), (Haiden et al., 2011) observation data set, which was used as it represents the analysis and nowcasting system of the Austrian weather service and integrates all available data sources: surface observations, remote sensing data, numerical weather prediction models, and a high-resolution digital elevation model, to produce an optimized representation of the current state of the near-surface atmosphere. This multi-source approach can be conceptually understood as an adjustment of a gridded background field using observational data. INCA is employed in applications such as flood warning and forecasting, as well as serving as the foundation for web portals providing spatially and temporally detailed meteorological information. The analyses contained in this dataset feature a spatial resolution of 1 km × 1 km and a temporal resolution of 1 hour. The heavy precipitation event responsible for the pluvial flooding on 29.07 is classified as an event with 30-year return period. To calculate the return period, a pareto distribution is fitted to the historical period of the daily INCA precipitation. Using the event's mean precipitation of 31.67 mm / day delivered a percentile of 96.3% which is approximately a 30-year return period (96.667%).

The INCA data also has been chosen as external forcing regarding precipitation over the catchment for the SFINCS model. Additionally, the river level and discharge measurement (ID 203075) in Mittersill is used as input for the discharge of the Salzach at the boundary of the domain. This information is provided by the Federal Ministry Agriculture and Forestry, Climate and Environmental Protection, Regions and Water Management and downloaded from their web portal eHyd (ehyd.gv.at). The digital elevation model (DEM) used has a spatial resolution of 1 m² and was obtained from the open governmental data (OGD) webpage (https://service.salzburg.gv.at/ogd/client/). Using the deltares hydromet-sfincs python package, the hydrological variables flow direction, river upstream areas, stream order and slope, necessary to run SFINCS, are calculated. The package is also used to set up the SFINCS model for the selected domain (Eilander et al., 2023).

To assess and estimate how climate change affects the intensity of such an event, the WRF climate model data produced in the HEU project ICARIA (Büegelmayer-Blaschek & Hasel, s. f.) was used. In a first step, the daily precipitation for the near-, mid- and far future period is fitted to a pareto distribution. Because the precipitation of climate models differs from reality and wet or dry biases apply, the amount of daily precipitation for a 30-year event from the climate model's historical period was calculated and searched for the climate change signal of this return period in the future periods of the climate projection. The climate change signal is then imprinted on the INCA data of the event in 2014 as well as on the discharge data of the Salzach river and used as external forcing in SFINCS. This process has been done for the return period 2, 30 and 100 for the SSP126 and SSP585 scenario using the climate change signal of the climate projections initialized with the CMIP6 MPI-ESM1-2-HR global circulation model (GCM) as lateral boundary data.

Model Calibration and Validation

To validate and calibrate the model, the following data sources were available:

- water level as measured within Mittersill (**Figure *27***) to ensure that the river bathymetry is correctly integrated and the runoff from the surrounding is realistically included
- hazard zone map of the regions (**Figure *28***): the hazard zone mapping process in Salzburg follows a structured methodology defined by Austrian guidelines for natural hazard management. It begins with data collection and analysis, incorporating hydrological, hydraulic, and geomorphological information to characterize flood, torrent, and avalanche hazards. Using high-resolution terrain models and historical event documentation, design scenarios are developed for events of varying return periods (e.g., 30-, 100-, and 300-year floods). These scenarios are simulated through hydraulic and torrent models to delineate areas subject to inundation, erosion, or deposition. Based on these simulations, hazard zones are classified into red zones (areas with high danger and prohibited development), yellow

zones (moderate danger with restrictions), and additional zones for residual risk or special conditions. This map is used for validation of the simulated flood event, since there was no observed flood depth map available.

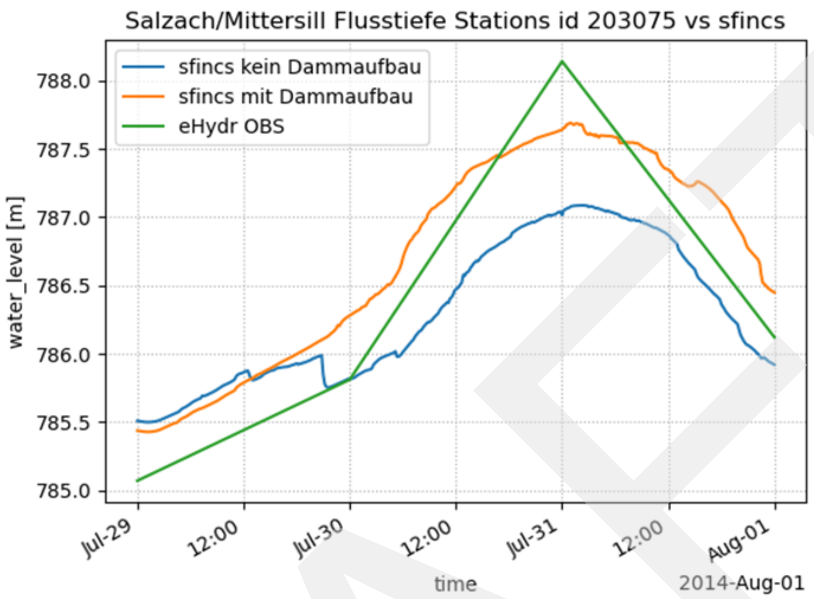


Figure 27. Water level at the station in Mittersill for the past event as observed (green), as simulated with SFINCS without already built adaptation measures already implemented and with the apparent measures included (orange).

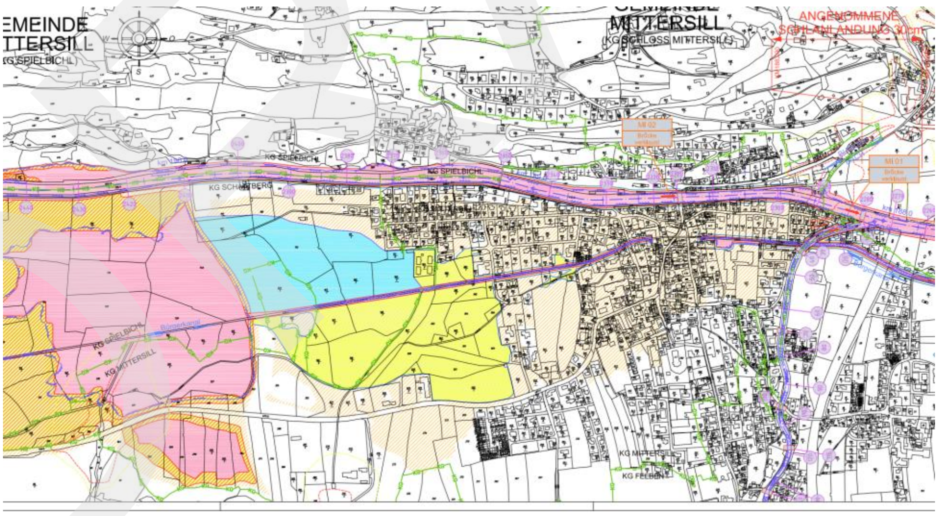


Figure 28. Hazard map of the simulated region (Pinzgau, Mittersill)

Red area represents areas where no buildings are allowed, yellow/red represents areas that are meant for retention, blue represents areas that are only allowed to be used for specific use, yellow areas represent areas that might be affected and should not be used for buildings or infrastructure, light orange represents 300yr return period extent

For the impact assessment validation, the event of 2005 provides some qualitative insights. Extreme precipitation intensities, representative of a 100yr return period, caused large scale flooding. Qualitative information on damage within the region is available through public reports on the event. In 2005, the flooding affected the whole part south of the Salzach, including the hospital which also led to the extreme damage value.

4.2.1.2. Windstorm single hazard model

Model context

During the first CoP, windstorms were identified as a climate hazard of interest to the regional stakeholders. The main effect of windstorms is on buildings being damaged and trees being dismantled, an effect that is further intensified through climate change related heat stress that weakens the forests. Further, the electrical system is impacted either through direct wind effects on the towers or through fallen trees on the lines. Since there is only information on the location of the trees, but not other aspects that determine their tendency to fall during windstorms (e.g., their height, type, age etc.), we didn't incorporate the latter into the analysis.

Model scope and objective

To assess windstorm hazard, the direct model output of the regional climate model simulations performed for SBG (D1.2) were used. Thus, the hourly wind speed and wind direction data is used, based on WRF and CLM regional climate models.

Model Calibration and Validation

Wind observations are only available from the observation network, representing very localized information. Past events have shown that damage on trees and roofs occur for wind speeds > 60 to 70 km/h.

4.2.3 South Aegean Region CS hazard models SAR

South Aegean Region (SAR) Trials are implemented in two islands separately. These Trials focus on Wildfires on the island of Rhodes and Heatwaves on the island of Syros. The architectures are presented in **Figure *29*** and **Figure *30***, below.

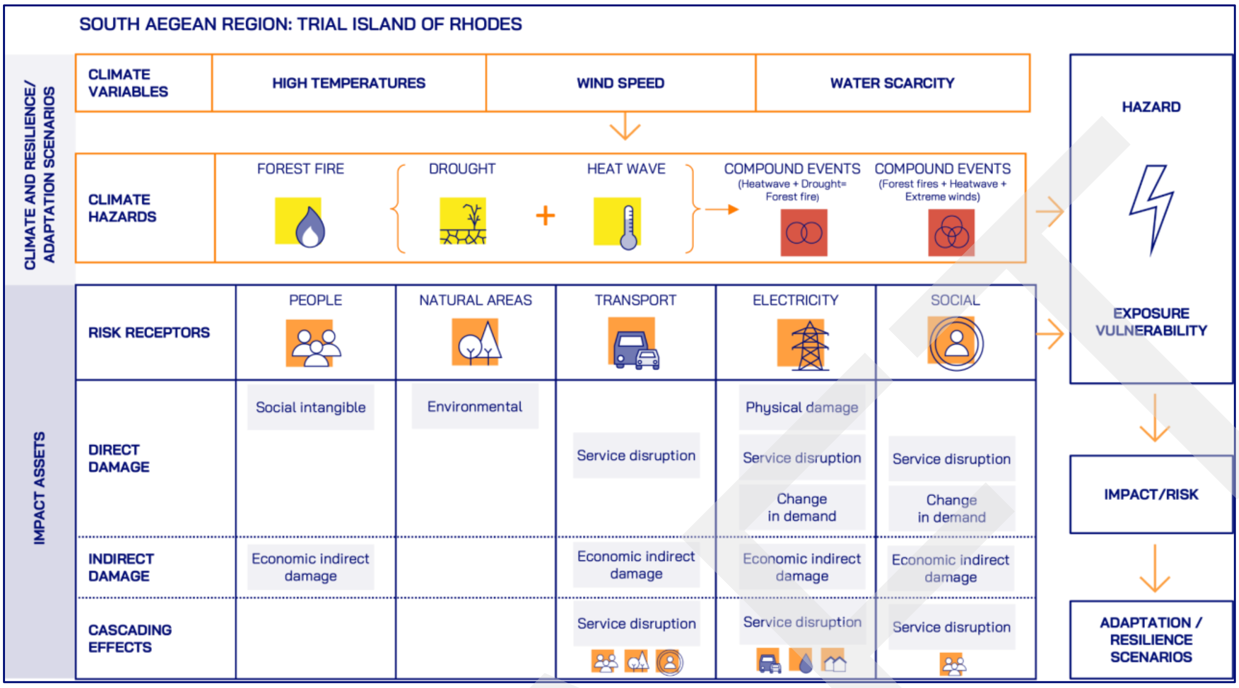


Figure 29. SAR Rhodes CS trial architecture

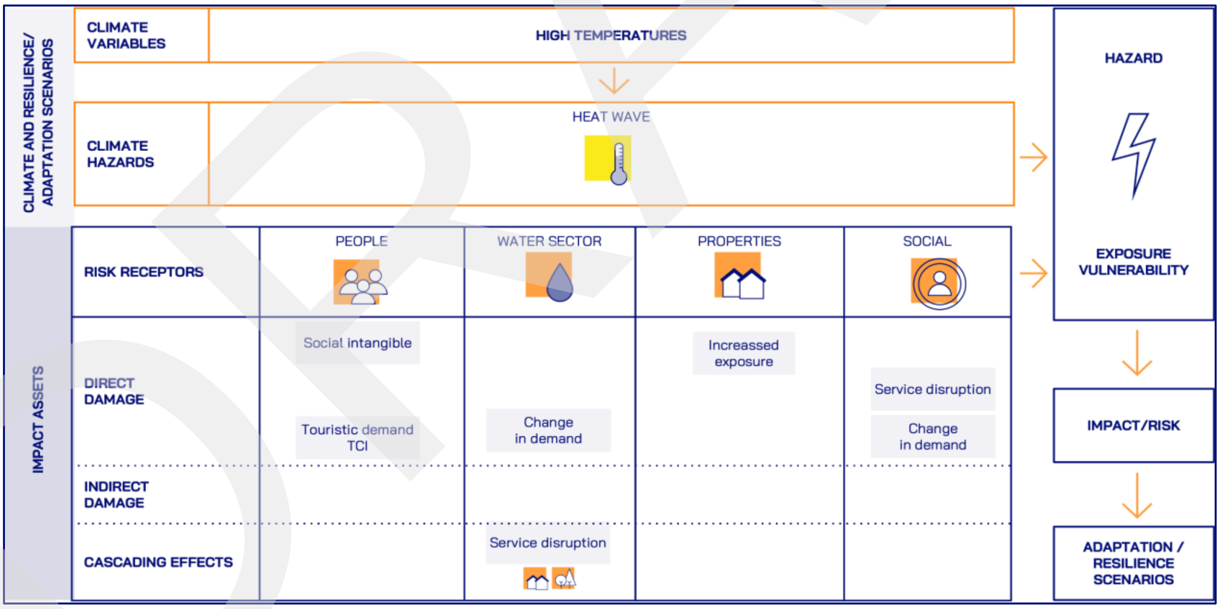


Figure 30. SAR Syros CS trial architecture

Wildfire Risk assessment methodology

The methodology for the wildfire risk assessment is divided in 3 steps, as shown in **Figure *31***. During the first step the wildfire hazard is estimated on the combination of Fire Weather Index (FWI) (Hazard) and Fuel Type (FT) maps. The wildfire exposure and vulnerability are estimated for People; Ecology; Critical Infrastructure (CI) and buildings, classifying the targeted elements at risk with respect to the likelihood of suffering a given damage level based on hazard intensity, according to available literature. Based on the results of the first two steps of the methodology, the risk assessment is performed as a probabilistic convolution of the H-E-V variables. Finally, impact assessment was performed for the Case Study area with a focus on reparation costs for CIs and buildings, based on historical data from previous wildfires.

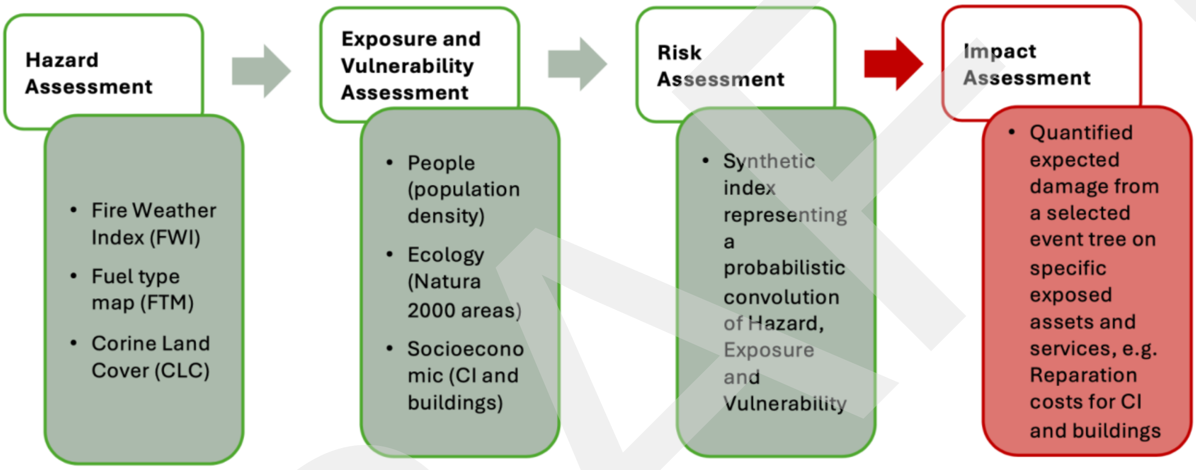


Figure 31. Risk and Impact Assessment Methodology Workflow Diagram

Fire Weather Index (FWI)

All FWI System components are calculated daily using four meteorological variables: precipitation, wind speed at 10 m, relative humidity, and maximum air temperature. FWI System fuel moisture codes are based on the previous day's conditions to reflect the cumulative effect of daily weather on fuel moisture. The calculated historical and future fire weather gridded datasets at 5 km for Greece (Rhodes Island included) are extensively described and analyzed for the Greek fire season, which spans from May to October. The components and structure of the FWI System are illustrated in the workflow diagram (**Figure *32***). **Table *15*** illustrates the classification of FWI values into fire danger classes for the European territory environments, as proposed by EFFIS. For this work, the number of days with very high fire weather danger was investigated with FWI >50.

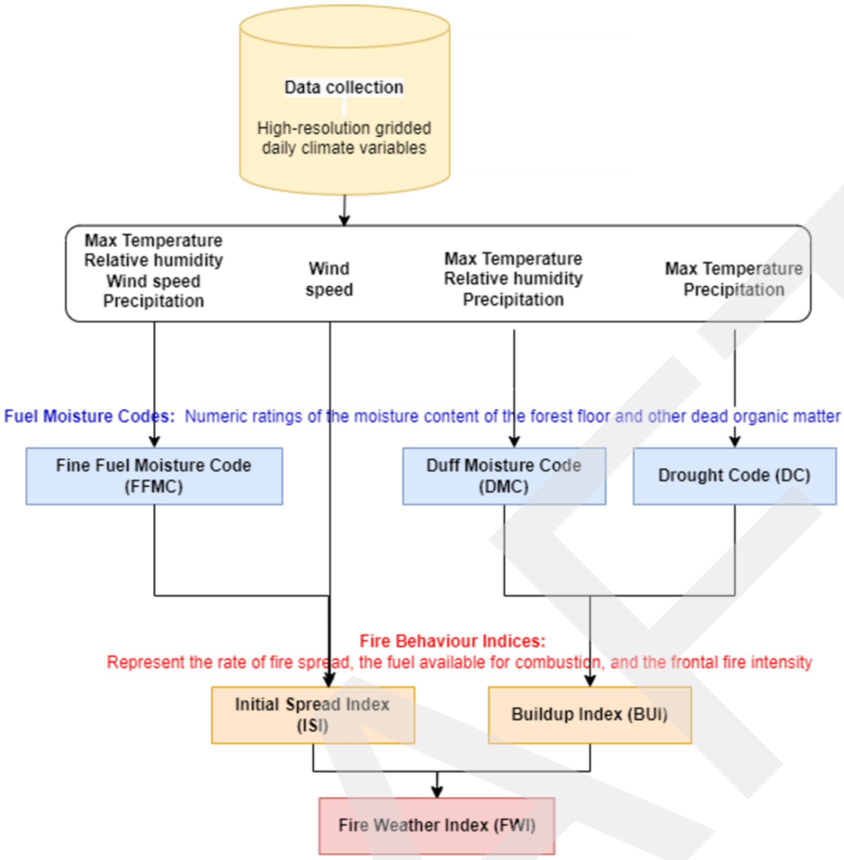


Figure 32. Structure and components of the Canadian Forest Fire Weather Index (FWI) System

Table 15. Classification of fire danger classes according to EFFIS.

Fire Danger Class	FWI
Low	< 11.2
Moderate	11.2 - 21.3
High	21.3 - 38
Very High	38 - 50
Extreme	50 - 70
Very Extreme	> 70

4.2.3.2 Heatwaves

The effect of heatwaves is directly linked to the heat stress on the CI and more specifically on buildings. For the quantification of this hazard, the European Standard EN 1991-1-5 is used. EN 1991-1-5 provides a methodology for determining thermal actions ("heat stress") on buildings from climatic and operational temperature changes, focusing on movements and stresses at ULS/SLS. This involves calculating uniform and difference temperature components using environmental temperatures, regional data, and heat transfer principles to represent realistic profiles. National Annexes specify key values like shade air extremes, tailored to local climates such as Greece's Mediterranean conditions.

Thermal actions give the principles and rules for calculating thermal actions on buildings, bridges and other structures, including their structural elements. Principles needed for cladding and other appendages of buildings are also provided. Thermal actions on a structure (or a structural element) are those actions that arise from the changes of temperature fields within a specified time interval. The main representative value of a given climatic action is its characteristic value, based on the probability of 0.02 of its time-varying part being exceeded for a reference period of one year. This is equivalent to a mean return period of 50 years for the time-varying part. This definition of the characteristic value, given in EN 1990 "Basis of structural design", is accepted in the relevant Parts of EN 1991 dealing with climatic actions. It is noted that the draft of EN 1990 for the second generation of the Eurocodes does not change the definition of the characteristic value of climatic actions. The characteristic values of thermal actions defined in EN 1991-1-5 used in the design of structures which are exposed to daily and seasonal climate change are:

- Tmax: maximum shade air temperature with an annual probability of being exceeded of 0.02
- Tmin: minimum shade air temperature with an annual probability of being exceeded of 0.02.

To calculate the return value for a 50-year period, data from the EC-EARTH Global Circulation Model was used, downscaled dynamically to 5 km spatial resolution with WRF. Data are available for three 25-year periods, the historical 1980-2004, the near future 2025-2049, and the far future 2075-2099. For the future periods, two scenarios of shared socioeconomic pathways have been obtained, SSP2 ("Middle of the road") and SSP5 ("Taking the highway"). For each year of each period, we compute the annual maximum temperature value, leading to time series of 25 values that we use to apply Generalized Extreme Value analysis to obtain the return value of the maximum temperature for 50 years.

The whole surface of the island is partially or entirely covered by 3 grid cells, from which we calculate the mean value for the whole island. To downscale to building level, we obtain Land Surface Temperature (LST) from the Landsat 8 – MODIS satellite dataset for 5 years (2021-2025). The dataset has 30 m spatial resolution. We obtain the shapefile with the buildings of Syros Island and apply the nearest-neighbor technique to assign a value to each building. We calculate the average LST of all buildings and then divide all buildings by that temperature to obtain a factor of difference from the mean value. Finally, we multiply each building factor by the return value for each period to obtain an approximation of heat stress on the buildings.

4.3 Risk assessment scenarios

The ICARIA risk assessments are based on the hazard models presented in Section 4.1, impact assessment methods presented in Deliverable 3.1 (Guerrero-Hidalga et al., 2024) and climate extremes indicators from Task 1.2 (Deliverable 1.2) (Paradinas Blázquez et al., 2024). This section is focused on the climate scenarios considered across the CS and the specific events considered in each risk assessment.

As mentioned, the climate inputs for the model are based on the outcomes of Task 1.2, which provides two key inputs. Firstly, historical extreme events intensity and frequency based on regional historic meteorological datasets. Secondly, it assesses the changes in intensity and frequency of such extreme events considering the different climate change projections in the IPCC AR6. Importantly, this involves the application of climate downscaling methods based on global climate model output representing the different emission scenarios that are reflected by the Shared Socioeconomic Pathways (SSPs). Two downscaling approaches are applied in the ICARIA CS. Dynamic downscaling is used for the SBG and SAR case studies, while statistical downscaling is applied to the AMB and, again, SAR and SBG case studies. The resulting climate projections, documented in Deliverable 1.2, form the basis of the ICARIA risk assessments.

Both statistical and dynamical approaches evaluate the evolution of the mean climate as well as extremes. The statistical method was applied to four SSPs (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) across the three case studies. For each SSP, the statistical method uses outputs from 10 climate models. To account for the dispersion among climate models in the statistical downscaling results, climate extreme indicators are aggregated into percentiles. This process produces a large and complex dataset of climate projections and extreme indicators. The dynamical approach uses 2 Global climate models' output for two SSPs (1-2.6, 5-8.5), thus resulting in 4 simulations at high spatial and temporal resolution to align this dataset with regional stakeholder needs and project resources, the ICARIA risk assessment focuses on two SSPs: SSP1-2.6 and SSP5-8.5. These pathways represent optimistic (Paris Agreement) and pessimistic climate futures, respectively, and together capture the full range of plausible climate extremes considered in AR6, enabling the assessment of both best-case and worst-case scenarios.

The impacts of climate change on extremes also vary with the time horizon, with event intensity generally increasing further into the future. To capture this temporal evolution, risk assessments are conducted for three future periods: short-term (2015–2040 for AMB and SAR, 2021-2051 for SBG), mid-term (2041–2070), and long-term (2071–2100). These periods are evaluated relative to a baseline derived from historical observed data. A 30yr time window is chosen to ensure reliable trends can be detected and decadal climate variations are smoothed out.

4.3.1 Barcelona Metropolitan Area CS risk assessment scenarios

The AMB CS risk assessment scenarios are focused on pluvial and coastal floods, as single-hazards, plus combined pluvial-coastal floods as multi-hazards. The climatic data used in these assessments are the outputs of the statistical downscaling of climate projections for the AMB presented Deliverable 1.2 (Paradinas Blázquez et al., 2024) and additional relevant sources for the case study.

4.3.1.1 Pluvial floods risk assessment scenarios

The key element that defines the scenario under assessment in a pluvial flood modelling is the rainfall design storm, which is usually represented as a hyetograph (rainfall intensity vs. time). These design storms are derived from IDF curves, correlating rainfall duration and intensity for different return periods based on a long precipitation timeseries. The hazard of pluvial floods in the AMB has largely been studied at the municipal level in the AMB. Thus, there is a large amount of data and studies about precipitation extremes. For consistency with previous projects such as RESCCUE, the design storms selected to simulate historic rain events in the AMB are retrieved from the last urban drainage master plan of Barcelona (Ortiz et al., 2020). Importantly, these curves are taken by the regional administration as the reference for flood assessments. Furthermore, in Task 1.2, it is validated that rainfall intensity patterns in the CS area are homogeneous. Thus, the Barcelona hyetographs are applicable to the whole AMB. In more detail, these design storms are generated following the alternate block method for a duration of 160 minutes, split in 5 minutes blocks (see Figure 33). In summary, the historic rainfall events considered in ICARIA correspond to the PDISBA hyetographs for five different return periods: T1, T10, T50, T100 and T500.

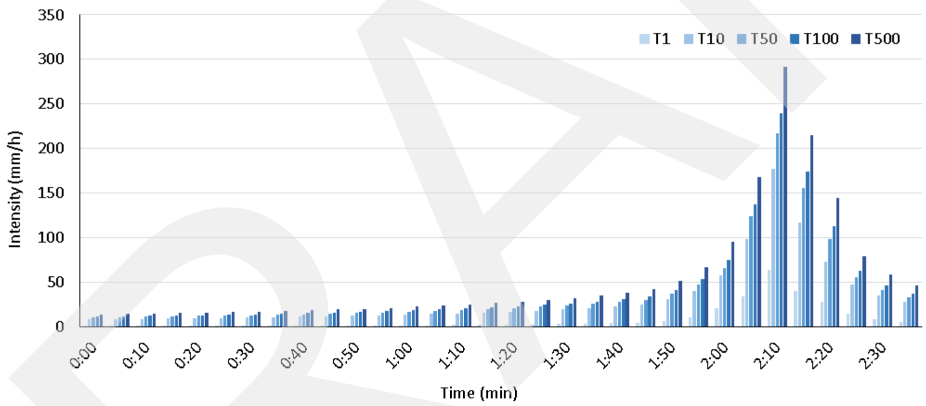


Figure 33. Historic hyetographs of PDISBA, considered as the historic rain events for the AMB CS

The hyetographs representing climate change scenarios are built as follows. As part of Deliverable 1.2 (REF), climate change factors (CCF) for rainfall intensity are available. These values

represent the growth in rain intensity for the different climate change scenarios and projection periods considered in ICARIA. Multiplying the historic IDF curves with the corresponding CCF gives a new IDF curve representing a specific CC projection from which hyetograph for CC scenarios are retrieved (see Equation 1).

$$\text{Intensity}_{\text{CC Projection}} = \text{Intensity}_{\text{Historic}} \times \text{CCF}_{\text{CC Projection}} \quad (1)$$

Table *16* shows the CCF corresponding to the maximum 5-minute intensity in the five return periods of interest for the three projection periods of SSP 1-2.6 and SSP 5-8.5 for the climate model ensemble corresponding to percentile 50. It can be observed that for SSP 1-2.6, the changes in extreme rainfall events (return period of 10 years and more) are little to non-significant. In consequence, the flood maps resulting from the SSP 1-2.6 hyetographs are not expected to be significantly different from the historic ones.

Table 16. CCF corresponding to the maximum 5-minute intensity in the five return periods of interest for the three projection periods of SSP 1-2.6 and SSP 5-8.5 for the climate model ensemble corresponding to percentile 50

Climate change scenario	Projection period	Climate change factor				
		T1	T10	T50	T100	T500
SSP 1-2.6	2015-2040	1.17	1.07	1.04	1.03	1.02
SSP 1-2.6	2041-2070	1.18	1.08	1.06	1.05	1.04
SSP 1-2.6	2071-2100	1.24	1.09	1.06	1.05	1.03
SSP 5-5.8	2015-2040	1.20	1.09	1.06	1.06	1.04
SSP 5-5.8	2041-2070	1.35	1.16	1.11	1.10	1.08
SSP 5-5.8	2071-2100	1.48	1.25	1.19	1.17	1.15

Taking all into consideration, the risk assessment scenarios considered for the single hazard pluvial flood are five historic rainfall events, corresponding to five return periods, and the projection of these events to the three assessment periods for SSP 5-8.5. This corresponds to a total of 20 events. Table 17 shows the maximum 5-minute intensity of each event.

Table 17. CCF corr Maximum 5-minute intensity for the 20 events considered in the pluvial single hazard risk assessments

Climate change scenario	Projection period	Maximum 5-minute intensity (mm/h)				
		T1	T10	T50	T100	T500
Historic		63.6	177.2	217.2	239.6	291.7
SSP 5-5.8	2015-2040	90.2	178.5	240.2	266.8	328.5
SSP 5-5.8	2041-2070	93.8	185.5	249.6	277.3	341.4
SSP 5-5.8	2071-2100	103.1	199.6	267.1	296.2	363.6

4.3.1.2 Coastal flood risk assessment scenarios

As reflected in Section 4.2.1.2, the coastal flood hazard assessment is multi-perspective, so it considers three different approaches.

The first approach is focused on the loss of land due to sea-level rise, which is the main model input. In consistency with the climate change scenario selection in Section 4.3, SSP 1-2.6 and SSP 5-8.5 are considered for the assessment. In this case, two different percentiles of statistical downscaling models are considered: 50th and 90th percentiles. **Table *18*** shows the mean sea level values corresponding to each scenario simulated.

Table 18. Mean Sea level rise associated with each climate change scenario and projection period

Climate change scenario	Mean sea level rise (m)					
	2015-2040	2041-2070	2071-2100	2015-2040	2041-2070	2071-2100
	Percentile 50th			Percentile 90th		
Historic	0	0	0	0	0	0
SSP 1-2.6	0.12	0.27	0.45	0.19	0.44	0.72
SSP 5-8.5	0.16	0.33	0.65	0.19	0.50	0.99

As for Approach 2 (which examines impacts on the coastal sewer pipe) and Approach 3 (which incorporates multi-hazard boundary conditions), different values are considered for the modeled scenarios. In both cases the assessment is based on the ESL values (main model input data) obtained from the coastal propagation of maximum wave height projections during storm surges. **Table *19*** shows the ESL value considered for each scenario.

Table 19. ESL associated with each climate change scenario and projection period

Climate change scenario	Projection period	ESL (m)				
		T1	T10	T50	T100	T500
Historic		3.05	4.06	4.40	4.54	4.85
SSP 1-2.6	2015-2040	2.99	4.28	4.67	4.82	5.14
SSP 1-2.6	2041-2070	3.19	4.20	4.55	4.69	5.00
SSP 1-2.6	2071-2100	3.18	4.15	4.47	4.59	4.87
SSP 5-5.8	2015-2040	3.25	4.17	4.45	4.57	4.82
SSP 5-5.8	2041-2070	3.17	4.11	4.46	4.61	4.94
SSP 5-5.8	2071-2100	2.92	4.12	4.52	4.68	5.03

4.3.1.3 Multi-hazard flood risk assessment scenarios

The multi-hazard flood risk assessment scenarios combine the design storm hyetographs (see maximum 5-minute intensity in **Table *17*** and the ESL in Table 19.

As part of Task 2.4, the University of Exeter has carried out a joint probability assessment of the coincident occurrence of extreme precipitation and storm surges in the AMB CS. It concludes that the limited historical record of storm surge events in this region does not allow for a conclusive assessment of the dependence between these extreme events. Considering this, the correlation between rainfall intensity and ESL has been simplified to simulate the same return period for both events. As in the single-hazard pluvial flood model, this assessment is focused on historic events and SSP 5-8.5.

Table 20. Correlation between rainfall intensity and ESL based on return period

Climate change scenario	Projection period	T1		T10		T50		T100		T500	
		5' I (mm/h)	ESL (m)	5' I (mm/h)	ESL (m)	5' I (mm/h)	ESL (m)	5' I (mm/h)	ESL (m)	5' I (mm/h)	ESL (m)
Historic		63.6	3.05	177.2	4.06	217.2	4.40	239.6	4.54	291.7	4.85
SSP 5-5.8	**2015-2040**	90.2	3.25	178.5	4.17	240.2	4.45	266.8	4.57	328.5	4.82
SSP 5-5.8	**2041-2070**	93.8	3.17	185.5	4.11	249.6	4.46	277.3	4.61	341.4	4.94
SSP 5-5.8	**2071-2100**	103.1	2.92	199.6	4.12	267.1	4.52	296.2	4.68	363.6	5.03

The ESL boundary conditions applied to the outfalls of the drainage models are adjusted to reflect the nature of extreme sea levels during storm surge events. ESL represents the maximum abnormal sea level reached at the shoreline, including the effect of waves, and is therefore not a constant value that can be prescribed as a fixed boundary condition. Explicit simulation of wave behavior is beyond the scope of this study and is not suitable for direct incorporation into a complex coupled 1D–2D model, as the rapid, second-scale fluctuations between wave peaks would induce highly variable boundary conditions and lead to numerical instabilities in the solution of the shallow water equations and the 1D–2D water exchange. To balance these modelling limitations while still capturing the influence of ESL on flooding in low-lying coastal areas, the boundary conditions are represented using a normal distribution, with the maximum value corresponding to the peak ESL (see **Figure *34***). The peak ESL is assumed to coincide with the peak rainfall intensity, ensuring that the combined effects of runoff interception, pipe backflow, and abnormal sea levels are represented at the most critical stage of the event.

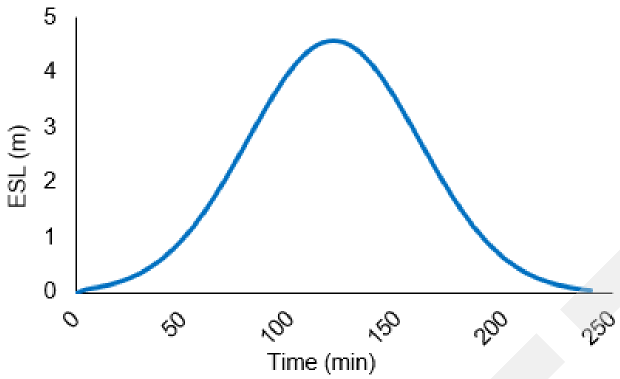


Figure 34. Normal distribution of the boundary conditions corresponding to the ESL event SSP 5-8.5 2015-2040 T10 with a maximum value of 4.57m

4.3.2 The Salzburg Region CS risk assessment scenarios

For Salzburg, the risk assessment was performed with the focus on extreme precipitation and windstorms. Therefore, the dynamically downscaled data was used as especially extreme winds are difficult to capture using statistical downscaling methods that rely on observation data.

Thus, two model (CLM, WRF) simulations are available for each SSP scenario and time period. The hourly model output was analyzed according to changes in intensity with respect to wind speed and precipitation intensity. For assessing flood intensities, the focus was on CLM, since the CLM model outperformed the WRF climate model with respect to precipitation validation. Nevertheless, both models were investigated for all periods to understand uncertainties in changes in precipitation intensity for the different return periods (

Table *21*).

Table 21. Summary time periods computed for SSP126 and SSP585 done for both regional climate models and return periods 2, 30 and 100 years.

SSP 126			SSP 585		
2021-2050	2041-2070	2071-2100	2021-2050	2041-2070	2071-2100
For flooding: T-2, T-30, T-100;					

As stated above (Section 4.2.2) to evaluate the influence of climate change on event intensity, daily precipitation for near-, mid-, and far-future periods was fitted to a Pareto distribution. Since climate model precipitation often exhibits wet or dry biases, the 30-year return period precipitation from the historical model run was calculated and compared to future projections to derive the climate change signal (**Figure *35***). This signal was applied to INCA data for the 2014 event and to Salzach River discharge, serving as external forcing for future events in SFINCS. The procedure was performed for 2-, 30-, and 100-year return periods under SSP126 and SSP585 scenarios.

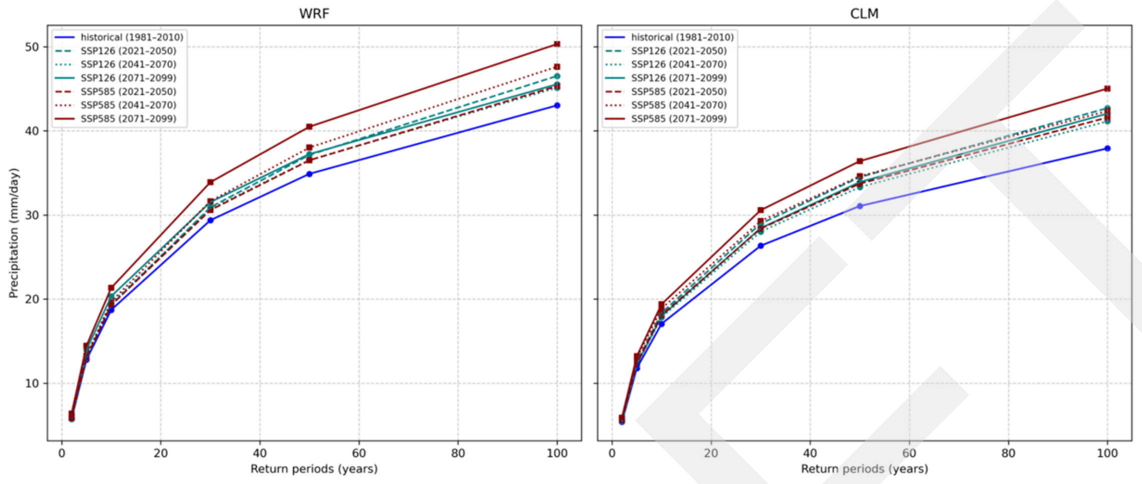


Figure 35. Return intensities of maximum precipitation intensities within 24h (mm/day) for the different SSP scenarios 1.5 (~Paris Agreement) and 8.5 (~worst case) as computed using the two regional climate models WRF and CLM (for more details please see D1.2)

Regarding wind speed, the output of WRF was used as it generally displayed higher wind speeds. As with flooding, both models were investigated in detail for all SSPs and time periods, with respect to mean changes and changes in return period intensities.

The analysis of the regional climate with respect to wind speed and direction doesn't display significant changes from the past period towards 2100, independent of the SSP scenario chosen. All events selected represent wind speeds corresponding to 100-year return period (**Figure *36***).

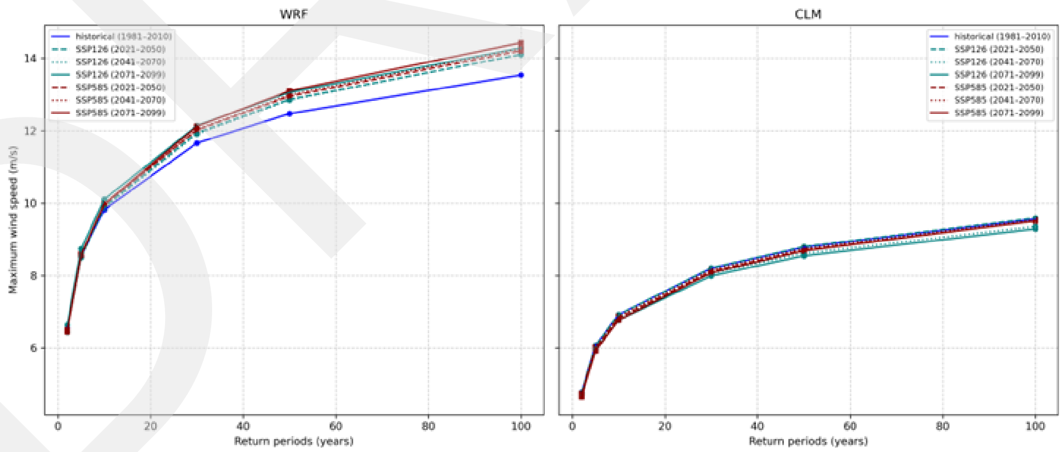


Figure 36. Wind speed (m/s) and return periods for the two RCMs averaged over the federal state of Salzburg

Wind direction during events with high wind speed depend on the region investigated, yet display a clear western component, with north-westerly, westerly and south-westerly directions (only for the region of Lungau shown, **Figure *37***).

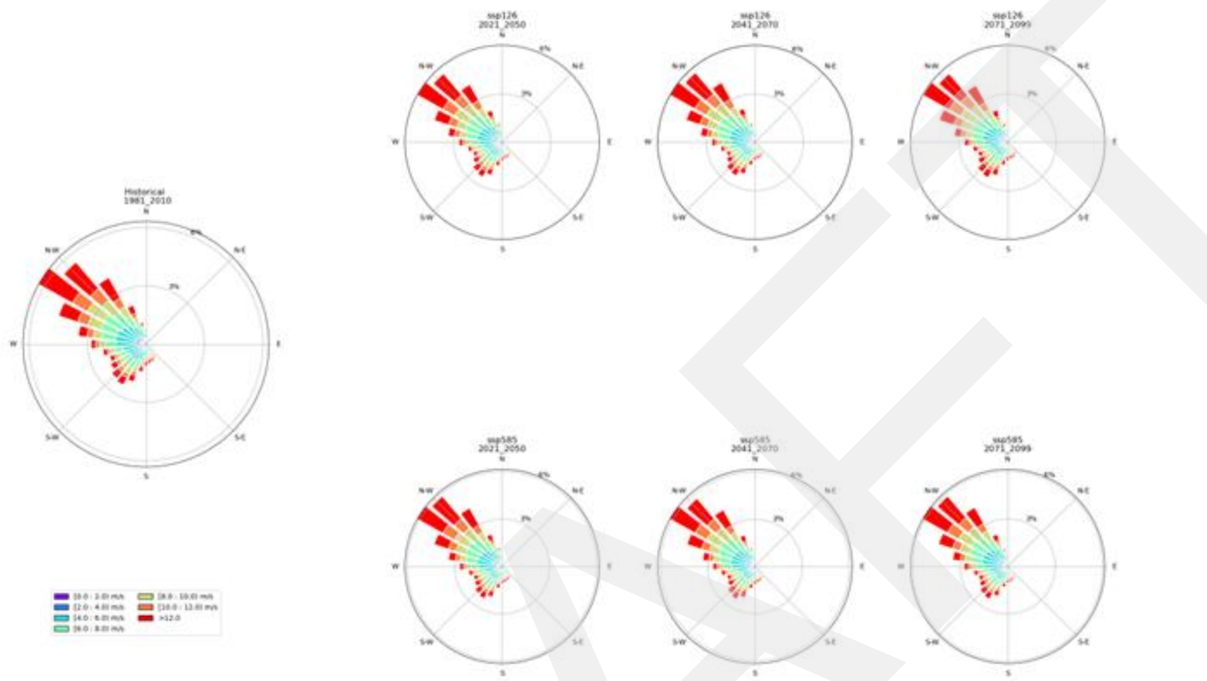


Figure 37. Planungsregion Lungau from WRF model Comparisons between scenarios and periods. Height-independent.

As was displayed above for the case study of Barcelona, each of the hazards studied derived based on different climate variables and time frames. Applying the results on hazard to specific exposures and vulnerabilities for relevant risk receptors provides the impact and risk information necessary to later build on possible adaptation and resilience scenarios and strategies.

4.3.3 South Aegean Region CS risk assessment scenarios

In SAR the risk assessment was performed with the focus on wildfires and heatwaves in two different islands of the region. Thus, the dynamically downscaled data (SSPs) for the region was used to calculate the risk for each hazard on the islands. Two SSP scenarios were used in the calculation of the indicators, linked to the hazards focused on the two locations.

SSP 126 - SSP 585
Periods: Historical and 2041-2070

As noted above, the hazard indicators were calculated for each climatic scenario:

1. Wildfires: Fire Weather Index (FWI)

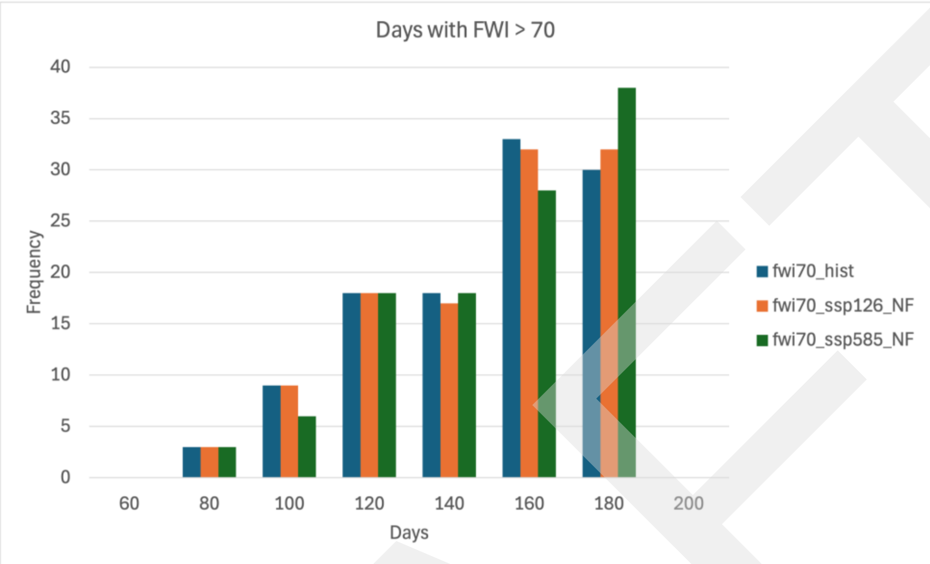


Figure 38. Histograms of FWI > 70 days for the difference scenarios implemented for the wildfire risk assessment of Rhodes Island.

2. Heatwaves: Heat Stress (HS)

Land Surface Temperature (LST) translates to heat stress on infrastructure by elevating surface temperatures on roads, buildings, and pavements, accelerating material degradation such as asphalt buckling, rail warping, and concrete cracking during heatwaves. High LST exacerbates urban heat islands where impervious surfaces retain heat, increasing energy demands for cooling buildings and straining power grids, while also inducing thermal expansion that stresses bridges and pipelines. This thermal stress serves as an indicator for infrastructure exposure to heatwaves. In this work the exposure is categorized in 5 categories based on the LST, calculated in the Trial islands.

- **Score 1:** <27.5 LST (Cº)
- **Score 2:** 27.5 – 30 LST (Cº)
- **Score 3:** 30 - 32.5 LST (Cº)
- **Score 4:** 32.5 – 35 LST (Cº)
- **Score 5:** > 35 LST (Cº)

4.4 Adaptation scenarios

4.4.1 Barcelona Metropolitan Area CS adaptation scenario

The Barcelona Metropolitan Area CS considers a single adaptation scenario with multiple adaptation measures focused on the hazard dimension of the implemented risk assessment framework. This section presents the rationale behind each one and how they are implemented in the baseline model used for single and multi-hazard risk assessment. It should be noted that, given the large scale of the flood model, all measures considered have a generalistic scope, so their effects are spread across the whole metropolitan area. Singular adaptation measures were not included in this assessment since their adequate dimension and implementation in the model would require small-scale feasibility studies beyond the scope of the project.

The adaptation scenario considers a set of nature-based solutions and sustainable urban drainage systems that aim to achieve a series of purposes in terms of water quantity reduction (reducing and delaying runoff and related peak of the hydrograph), water quality improvement, and enhancing biodiversity and amenity. In the following sections, details about these measures and the modelling approach to simulate their hydrological effects are presented.

Porous pavements

The AMB authority is currently promoting the implementation of porous pavements in the bike lanes and slow-speed single-lane streets, known as "Zone 30" in different locations in the region (Olivares-Cerpa et al., 2022). These pavements can virtually drain extreme rainfall intensities much larger than those considered in the simulations in Section 4.3.1. The AMB has a total length of 9.084 km of paved streets, corresponding to 637,4 km^2. Out of the total, 2.930 km correspond to Zone 30 areas and 331 km of streets in the AMB host bike lanes. Considering an average width of 1.5 m for care and double bike lanes, the potential area for porous pavement implementation in the AMB is 58,1 m^2. Approximately, 9% of the total current street area.

Figure 39. Porous pavement for bike lanes project

Given that this pavement is expected to generate no runoff due to their high infiltration rates as demonstrated by a recent pilot executed in the city and some specific laboratory tests developed at the hydraulic laboratory of the Technical University of Catalunya (UPC) (Estrella et al., 2025; Olivares-Cerpa et al., 2022) , the implementation of this measure in the model is based on reducing the runoff contributing area of all street land use polygons by a 9%. This measure can have a relevant influence since its reduced runoff generation capacity is mostly located in urban areas, where flood damages are concentrated. However, it is acknowledged that this reduction of effective area is homogeneously applied to all streets in the AMB, while slow traffic and bike lanes are not equally distributed. The complexity of the model structure makes it difficult to represent this measure more accurately.

Green roofs

Green roofs are a well-known nature-based solution (NbS) to reduce runoff generation in urban areas. Despite being more adequate for the reduction of water volumes in ordinary rain events, their number is growing in the AMB. In particular, in public buildings such as schools, libraries, or municipal services, among others. The Barcelona City Hall promotes the development of these areas in the city[1].

Figure 40. A green roof in Barcelona («Xifré's Roof: "Floating" Wild Garden», 2019)

The AMB has a census of roughly 7.500 public buildings totaling around 19 km^2, a 30% of the total roofed area in the AMB. Considering a safe assessment, 10% of the public in the AMB are considered to be totally covered by green roofs. The percentage is consistent with studies on the feasibility of green roof implementation in the city of Barcelona (Locatelli et al., 2020; Velasco et al., 2016) The selection of these buildings is proportionally distributed among the 36 municipalities. In terms of modelling, the characteristics of green roofs are represented as an additional type of land use for the sub-catchments involved. Specifically, the fixed initial losses are defined as 7mm instead of 3mm, as in regular roofs. In addition, the Manning roughness is 0,4 instead of 0,015. These parameters represent the double effect of runoff reduction and peak delay associated with this type NbS. The key assumptions involved in modelling this adaptation measure are the semi-random distribution of green roofs and the consideration that the selected buildings are fully covered by them.

[1] https://ajuntament.barcelona.cat/ecologiaurbana/en/green-roof-competition

Bioretention areas

Inner patios are very common in the urban matrix in the AMB. The baseline model of the AMB considers that all built parcels are fully impervious and drain directly into the closest node of the sewer network. However, a local scale assessment reveals that configurations are multiple. In the area of study, the number of green inner patios is growing. The last urban master drainage plan of Barcelona (PDSIBA) identified that these areas have a large filtering capacity and reduce the imperviousness in densely urbanized areas The PDISBA envisages Barcelona being equipped with a total SUDS surface area of 180 ha, strategically spread around the city, a set of retention ponds in the Collserola area, and a development plan for green roofs on buildings (Ortiz et al., 2020). A regional assessment of the AMB shows that 7,3 km^2 can potentially become bioretention areas and minimize their runoff contribution.

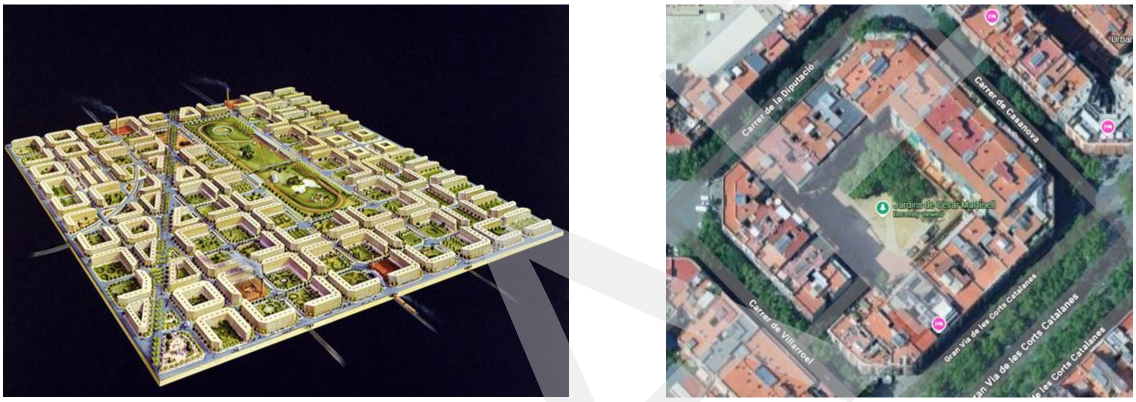


Figure 41. Representation of potential bioretention areas in Barcelona

The implementation of this adaptation measure is as follows. Firstly, the total roof and inner patio areas of each building in the AMB are calculated. Next, in the cases where inner patios exist, the patio area is subtracted from the contributing area of the corresponding sub catchment. At a metropolitan scale, this corresponds to a reduction of 12% of the total roof contributing area.

In summary, a total of 3 adaptation measures are considered for this scenario in the AMB CS.

4.4.2 Salzburg Region CS adaptation scenario

For Salzburg, specifically the Mittersill region, three different adaptation measures are investigated, two with respect to the risk related to fluvial flooding on properties and traffic, and one with respect to windstorm risk on properties.

Relocation of buildings

Relocating industrial buildings out of flood-prone areas is an adaptation measure within flood risk management that reduces exposure of infrastructure and economic assets to flood hazards by avoiding development in high-risk zones or moving existing facilities to safer ground. This aligns with broader land-use planning and managed retreat strategies, which seek to limit exposure and potential damages from floods by steering development away from hazard zones or withdrawing assets when risks become intolerable. Co-benefits include lower long-term economic losses, reduced business interruption, improved worker safety, and fewer demands on emergency response and recovery funding. Strategic relocation also frees floodplains for natural water retention, potentially enhancing ecosystem services. Risks and challenges encompass high upfront costs, logistical disruption, potential loss of local jobs and supply chains, land availability constraints, and social resistance from stakeholders attached to existing sites. Careful planning, stakeholder engagement, and integration with broader flood management policies are essential to realize benefits. Within Mittersill, an industrial site is located within the flood zone, therefore being highly affected and controversially discussed whether to keep or relocate it. Therefore, one adaptation scenario evaluates the reduction in damage in case these buildings were relocated.

Early Warning System

Early warning systems (in the SBG case study for floods) generate substantial co-benefits beyond preventing fatalities by enabling earlier, better-targeted decisions across households, businesses, and public services. When warnings are credible and actionable, they trigger “early action” (e.g., temporary flood barriers, moving vehicles and stock, protecting utilities, pre-positioning responders), which reduces disruption time and the indirect economic impacts that often exceed direct damage. Evidence syntheses consistently find high economic efficiency: the World meteorological organization (WMO) highlights that early warning systems are cost-effective and can deliver close to a tenfold return on investment. Early warnings also support better municipal operations and planning by strengthening monitoring networks, risk communication, and coordination protocols—capabilities that spill over into broader emergency management and climate adaptation. Practically, even short lead times can pay off: United Nations Environment Program (UNEP) summarizes evidence that 24 hours’ notice can reduce damage materially (https://www.unep.org/topics/climate-action/climate-transparency/climate-information-and-early-warning-systems). The impact of an early warning on car usage is analyzed to estimate the reduced impact of flooding on traffic.

Enhanced Building Structure

Enhancing building structure (e.g., stronger roof-to-wall connections, improved lateral load paths, impact-resistant openings, and compliance with wind-resistant codes/standards) is a well-established adaptation measure against windstorms because it reduces vulnerability to hurricane/strong-wind hazards. The co-benefits can be material: modern, hazard-resistant building codes demonstrably reduce losses from hurricane winds at relatively modest incremental construction cost, improving household financial resilience and lowering recovery burdens on insurers and public budgets. Where code upgrades are bundled with “green building” provisions and better accessibility, they can also improve everyday safety, comfort, and inclusivity, creating broader development benefits beyond storm events (World Bank, 2025). However, potential net harms exist. First, stronger structures often require additional materials and retrofitting activities that can increase embodied greenhouse-gas emissions unless low-carbon material choices and whole-life design are prioritized (IPCC, AR6 (IPCC, 2023b) WGII - Cabeza et al., 2022l). Second, higher upfront costs and uneven enforcement capacity can shift burdens onto lower-income households or landlords, potentially widening inequities or incentivizing informal/unsafe workarounds if financing and compliance support are absent. Finally, overreliance on "code compliance" can create complacency if residual risk (extreme events beyond design levels) is not communicated and integrated into preparedness and maintenance regimes.

The impact of windstorms on Mittersill is evaluated under the assumptions that the prevailing houses are upgraded to higher standards.

4.4.3 South Aegean Region CS adaptation scenario

The South Aegean Region CS consists of two major islands: Rhodes and Syros. The islands are affected by different climatic hazards. Rhodes is affected by Wildfires, while Syros is affected by heatwaves. Thus, the adaptation measures are different in the two islands. The solutions evaluated are based on the outcomes of the CoP events that took place in both islands.

Rhodes: Reforestation

Reforestation on Rhodes Island involves a strategic, managed planting of species to speed up recovery after fires and reduce future wildfire risks. The focus is on establishing drought-tolerant, fire-resistant native species in recently burned and degraded areas where natural regeneration is insufficient. The Carob tree (Ceratonia siliqua) is included as part of a diverse species mix rather than the sole reforestation species, enhancing ecological resilience and maintaining landscape diversity while avoiding dependence on a single species. The strategy also includes creating fire-safety zones—such as fuel breaks and green buffers—around settlements, infrastructure, and valuable ecosystems. These zones often feature low-flammability species like Carob along edges or within mixed belts to break up continuous fuel loads, slow fire spread, and support firefighting efforts. Through combined efforts of managed reforestation and strategically placed fire-safety zones, the plan aims to prevent soil erosion, increase carbon storage, and develop a more resilient, climate-adaptive forest landscape capable of better resisting wildfire hazards heightened by climate change.

Rhodes: forest conservation

The transformation of forests on Rhodes Island is conceived as a strategic transition from predominantly combustible, uniform pine stands to more fire-resilient and climate-adaptive forest configurations. This approach involves an expanded utilization of the Carob tree (Ceratonia siliqua) and other indigenous, low-flammability species characteristic of the Aegean and Mediterranean regions. The Carob tree is emphasized as a pivotal element of the revised stands owing to its extensive root system, high tolerance to drought and salinity, dense canopy, and relatively low flammability. These attributes contribute to reducing surface fuel continuity and limiting the spread of fires. It is integrated with other relatively resistant species such as Mediterranean cypress (Cupressus sempervirens), Fig trees (Ficus carica and Fig opuntia), and Black-locust (Robinia pseudoacacia) in urban and peri-urban areas, provided they are managed to maintain open crowns and low understory fuel loads. This transformation aims to prioritize areas where pine monocultures pose significant wildfire risks to communities, infrastructure, and sensitive ecosystems, by gradually replacing them with mixed stands that combine Carob-dominated belts with patches of broadleaved and sclerophyllous species. The resulting landscape is engineered to establish natural fuel breaks, augment moisture retention within the understory, and enhance post-fire regeneration capacity, thereby decreasing fire intensity and bolstering long-term ecological resilience. Over time, such forest conversion is anticipated to augment carbon sequestration, mitigate soil erosion, and support biodiversity. Furthermore, it aims to sustain or improve the socio-economic value of forests through multifunctional land uses such as agroforestry, non-timber forest products, and sustainable tourism.

Syros: Retrofit housing for adaptation

Retrofitting the existing housing stock on the island of Syros represents a critical adaptation measure to reduce heat stress (HS) during increasingly frequent and intense heatwaves under a warming Mediterranean climate. Emphasis will be placed on housing units constructed between 1980 and 2010, a period that accounts for a significant share of Syros' residential building stock and is often characterized by limited thermal insulation and high heat-gain potential. The strategy focuses on improving the thermal performance of these dwellings through envelope-oriented interventions such as external or internal wall insulation, high-performance windows with solar control glazing, and cool roofs that reduce solar heat gain and surface temperatures, while ensuring that structural modifications do not compromise their existing seismic performance. Particular attention will be given to maintaining or enhancing structural integrity through non-invasive or lightweight solutions, avoiding heavy claddings or configurations that could alter load paths or increase vulnerability to earthquakes. Complementary measures, including shading devices, night-time ventilation protocols, and passive cooling techniques, will be integrated into the retrofit framework to attenuate indoor heat stress, lower cooling energy demand, and enhance adaptive thermal comfort for residents. By mainstreaming heatwave-resilient retrofit standards into local building renovation programs, Syros can strengthen public health protection, reduce energy-poverty pressures, and contribute to a more climate-adaptive urban environment without increasing seismic risk.

5 AMB Risk assessment results

5.1 Single-hazard risk assessment

5.1.1 Risk assessment of pluvial floods on properties

Risk assessment of PLUVIAL FLOODS on PROPERTIES

Risk assessment methodology

This assessment's goal is evaluating the potential economic damages to different kinds of properties within the Metropolitan Area of Barcelona (AMB). The risk framework combines hazard, exposure, and vulnerability components to estimate expected economic losses. The assessment was done for different scenarios and return periods, according to the economic flood damage assessment method applied to properties explained in the Deliverable 3.1.

Hazard assessment on PROPERTIES

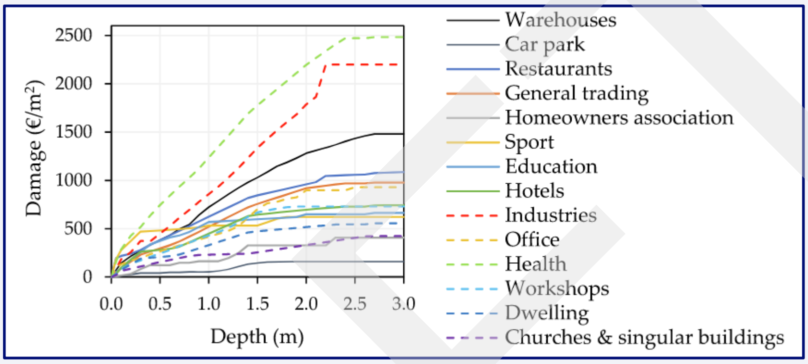
The hazard assessment is focused on urban pluvial flooding modeling to identify flood prone areas, water depth and velocities during extreme rain events. This is achieved through a 1D/2D hydrodynamic model developed with the Infor works ICM software. In this model, 1D sewer flow and 2D overland flows are computed and interact in the considered domains providing results on both domains (underground and surface). For this case of assessment, according to the mentioned method, only 1D water depths on the surface 2D domains transferred to the buildings/parcels according to the flood damage model developed within RESCCUE (Martínez-Gomariz et al., 2021), are considered.

Exposure assessment on PROPERTIES

The exposure of economic value on properties of the AMB is characterized by the locations and area of buildings in the studied area. For this assessment, a map of all buildings in the AMB was used. Due to the large surface and the detailed goal of the analysis, this map was later reduced to keep only buildings that have ground floor and/or basements. Due to data privacy issues, economic damages were also grouped by census areas and districts according to the policy followed in the last Drainage Master Plan of Barcelona (Ortiz et al., 2020; Russo et al., 2020).

Vulnerability assessment on PROPERTIES

Vulnerability was characterized using flood depth-damage curves specifically created for the Barcelona Metropolitan Area. These were developed by combining semi-empirical analysis of real flood insurance appraisal data from Barcelona with expert judgment from an experienced insurance team, resulting in depth–damage relationships. Where observed data were sparse, the curves were completed and smoothed using expert opinion to reflect realistic damage progression with increasing indoor water depth (Martínez-Gomariz et al., 2021). These curves consider fourteen different land use types, which corresponds to the same classification used by the Spanish "Catastro" to classify the land use of buildings. Each of these curves correlate the water depth inside the building with the expected economic damage in the property. Through a GIS procedure, water depth inside each building for the AMB is determined based on the flood (hazard) maps. A second process correlated hazard parameter (flow depth inside the building) with the total monetary damage at building level (E. Martínez-Gomariz et al., 2019). Finally, results are aggregated in censal districts. Importantly, these curves were initially developed for the city of Barcelona. However, damages vary from municipality to municipality due to demographic and socio-economic characteristics, so Barcelona curves were adapted to the other 35 municipalities of the AMB by applying correction factors as presented in (Martínez-Gomariz et al., 2020).



Impact assessment results

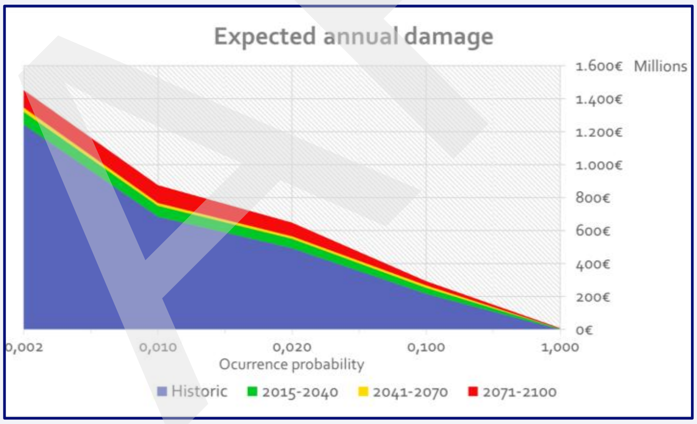
Flood damage caused by the selected rain events was calculated for each building in the AMB by multiplying the flood depth inside each parcel with the damage ratio from the depth-damage curves. This results in the direct economic costs for each building for four different time horizons (Historic, 2015-2040, 2041-2070 and 2071-2100) and five periods (T1, T10, T50, T100, T500). In total 20 rainfall scenarios are considered. Combining the damages for all buildings, total damages for the AMB are obtained. The results in the following table reflect these numbers. Under the current rainfall patterns, the AMB faces economic damages from 217M € for a T10 event, to 1.200M€ for T500. According to the climate change projections considered, these damages could rise 35% and 16% for T10 and T500 events respectively.

Regarding the T1 events, it can be observed that the raise in economic damage is especially drastic. As shown in Table 20, the changes in the peak in intensity of T1 events are percentually larger than for the higher return periods. In fact, the climate change factors applied are: 1.21 for the 2015-2024, 1.34 for 2041-2070, and 1.48 for 2071-2100. With these increases, the T1 events for the climate change projections correspond to a T2 or T3 event according to the historic IDF curves or Barcelona.

The Expected Annual Damage (EAD) is a probabilistic risk metric used in flood risk and urban resilience studies to estimate the *average economic loss per year* from flooding, accounting for all possible flood events and their likelihoods. It integrates two perspectives: "How often flood events happen" and "How much damage they can cause". This metric allows comparing current and future scenarios and is a standard approach used to evaluate the cost of no action (business as usual scenario) as well as the economic benefits (in terms of avoided damage) of adaptation strategies including a large set of type of measures (grey and blue-green infrastructures, no structural measures like Early Warning Systems, etc.).

The following table and figure reflect the evolution of this parameter for the modeled scenarios.

	Economic damage on properties for the return periods considered (and percentage of increase with respect to historic event)					
Projection Period	**T1**	**T10**	**T50**	**T100**	**T500**	**Expected annual damage**
Historic	11,593€	217,355,156€	492,957,585€	685,123,061€	1,244,155,564€	139,835,064 €
2015-2040	4,396,532€	252,180,343€ (+16.0%)	551,263,006€ (+11.8%)	750,289,.090€ (+9.5%)	1,319,745,346€ (+6.1 %)	162,385,226 € (+16.1%)
2041-2070	4,821,447€	267,754,177€ (+23.2%)	565,422,499€ (+14.7%)	766,971,837€ (+11.9%)	1,344,925,267€ (+8.1%)	171,095,658 € (+22.4%)
2071-2100	7,784,126€	293,807,760€ (+35.2%)	648,675,358€ (+31.6%)	876,513,560€ (+27.9%)	1,451,254,519€ (+16.6%)	190,352,690 € (+36.1%)



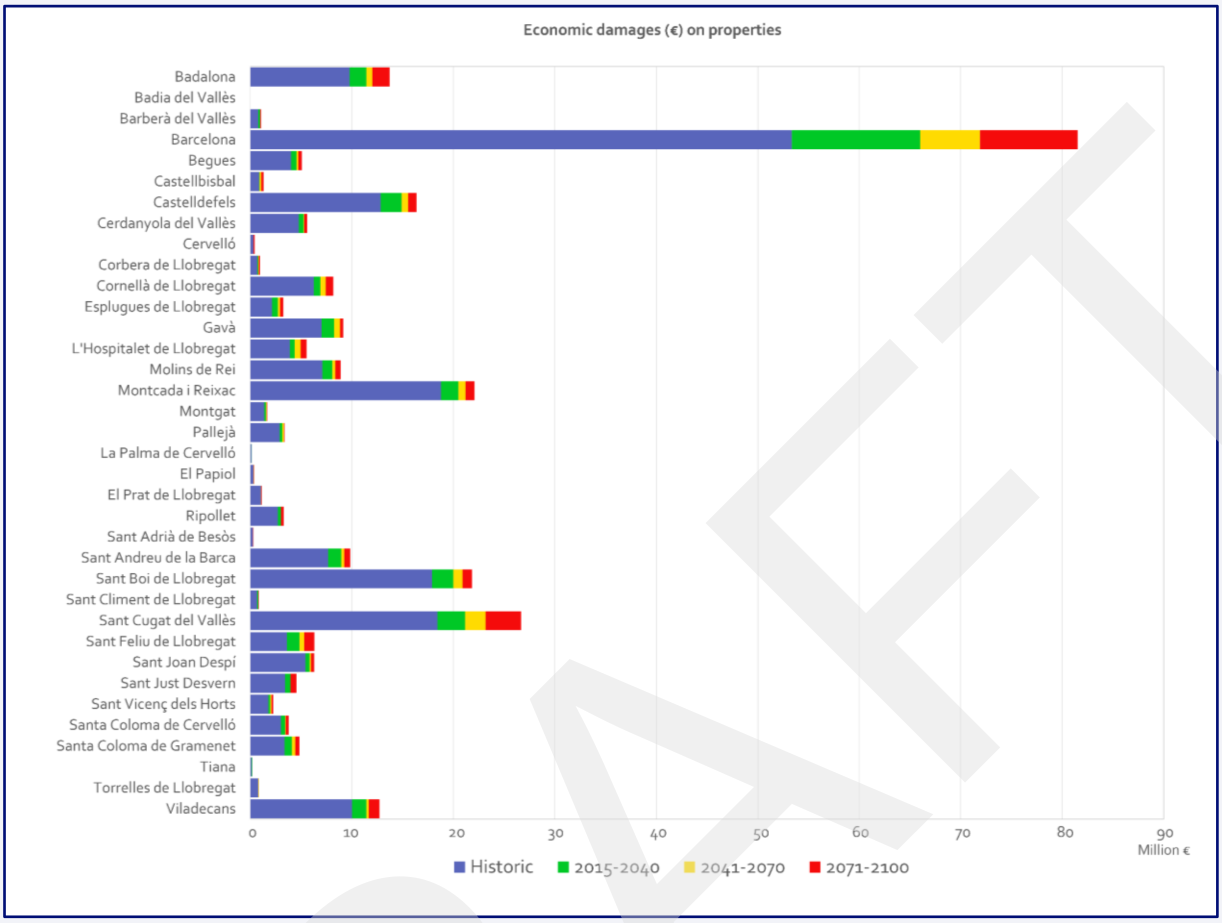
Results show that the EAD associated with the historic rainfall events can rise from 139M€ to 190M€ by the end of the century, meaning a 36% increase. This growth is particularly severe between the mid-term and the long-term projection periods. This is consistent with the corresponding climate change factors and the resulting severity of the flood maps.

However, it is important to mention that the percentage increase in rainfall intensity (from 5 to 20% depending on the projection period and return period) is less than the increase in economic damages (up to 35%). This is due to the level of protection provided by existing infrastructure (generally, in urban drainage, related to a return period of 10ys), which means that all excess runoff produced above this threshold that cannot be drained by existing drainage systems is converted in uncontrolled flow with significant social and economic impacts in the considered municipalities.

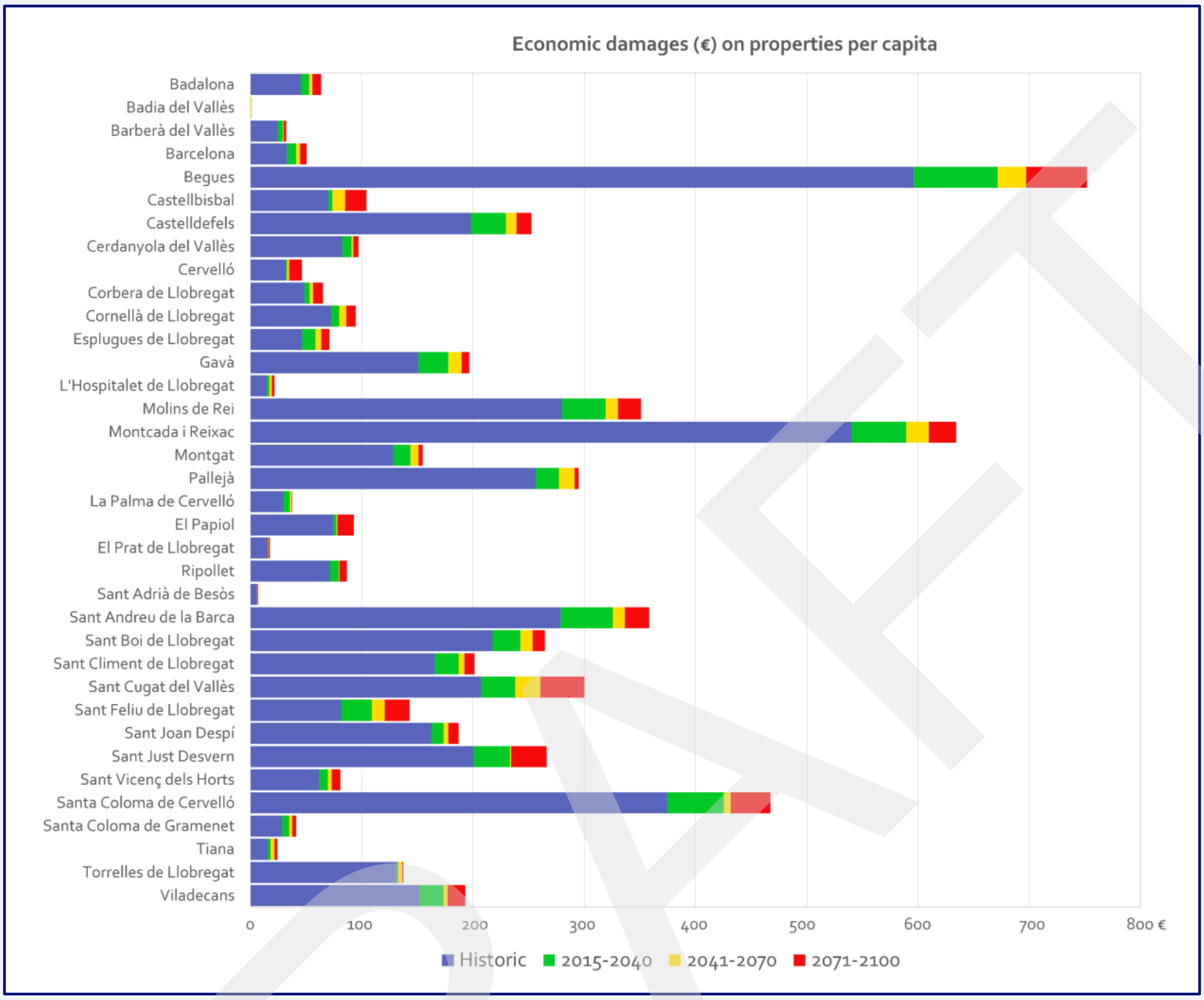
In comparison with previous studies, project RESCCUE concluded that the economic impact of a historic T10 event in the city of Barcelona is approximately 52M€ (Russo et al., 2020). According to the ICARIA results, this same event can cause 53M€ of damage in the city. Since the damage quantification methodology applied in both projects was the same, these differences are associated with the hazard dimension of the risk assessment. Remarkably, the ICARIA flood model is based on a hybrid approach where rainfall is directly applied to the non-structured mesh, which covers the whole model domain with the exception of the building roofs, which are modelled as sub-catchments. As a result of this, runoff is directly generated in the mesh grid elements and then transported on the 2D domain of the model. In this transport process, it may enter the sewer system or not. On the contrary, the RECCUE models considered a different approach. Runoff was generated in sub-catchments directly connected to the sewer systems. Thus, all the generated runoff was conveyed in the sewer. Water could only reach the urban surface when the pipes reached pressurized conditions and discharged through manholes. These methodological differences lead to different hydraulic behavior of the network and flood maps. Subsequently, the water levels in the area of study change from model to model, leading to the mentioned discrepancies in the economic impact assessment.

At the municipal level, findings show that Barcelona is the most affected municipality when analyzing total damage, with an estimated monetary loss of 81.5 M€ for an event with a return period of 10 years in the scenario described by the SSP 585 in the period between 2041 and 2070. The damage suffered by all other municipalities remains below the 30M € mark.
Although it is important to take into account total economic damage. It is expected that Barcelona, the biggest and with highest population and building density municipality in the AMB, would suffer much more economically than any other area. There are other territories such as Sant Cugat del Valles, Montcada i Reixac or Sant Boi del Llobregat that suffer high economic damages as well exceeding the 20M €.

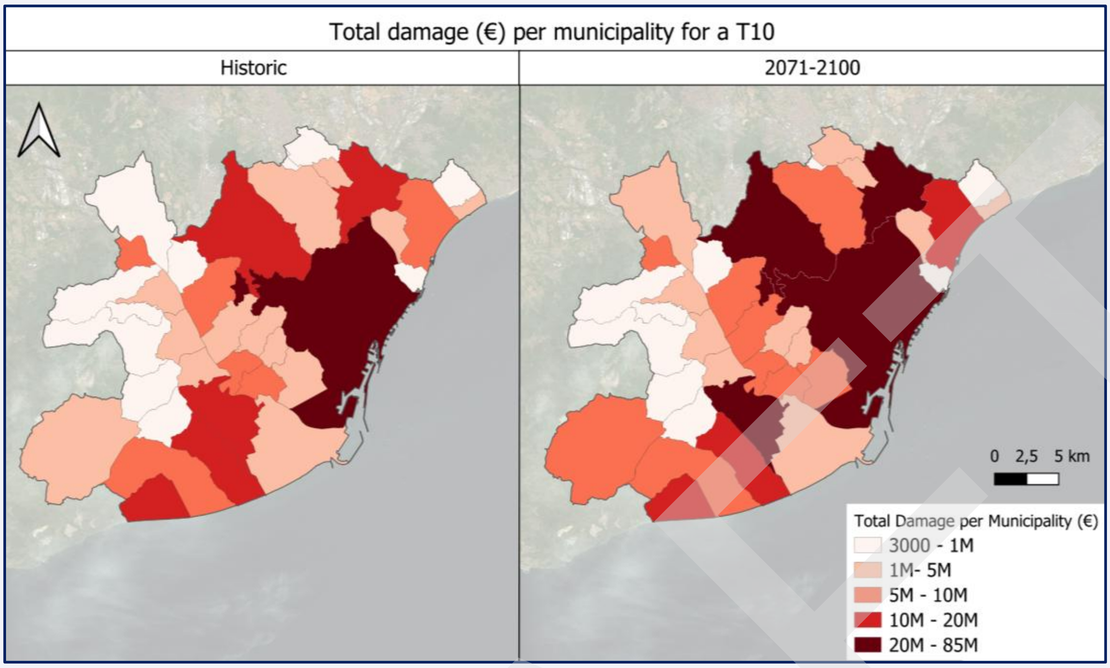
The figure below reflects the split of the total economic damage in the 36 municipalities of the AMB for the four T10 design storms simulated (historic, short-term, mid-term and long-term projections). The largest share corresponds to Barcelona, with 53M€ to the synthetic T10 historic event, followed by Sant Cugat del Vallès, Sant Boi de Llobregat and Montcada i Reixac, with cumulative damages of 22 to 27M€ for the same event. The majority of the municipalities do not reach 10M€ damages for the long-term projection T10 rainfall. These results align with a general principle: larger municipalities, with more buildings (assets) exposed, experience greater economic impacts from floods.



To consider another perspective, it is relevant to cross the economic impact data with the population size of each municipality. As shown in the following figure, when assessing the damages per capita, it is possible to see that some small municipalities such as Begues (751€/capita) or Montcada i Reixac (634€/capita) appear as the most damaged cases. The results in the following graph also correspond to the four T10 design storms simulated (historic, short-term, mid-term and long-term projections).

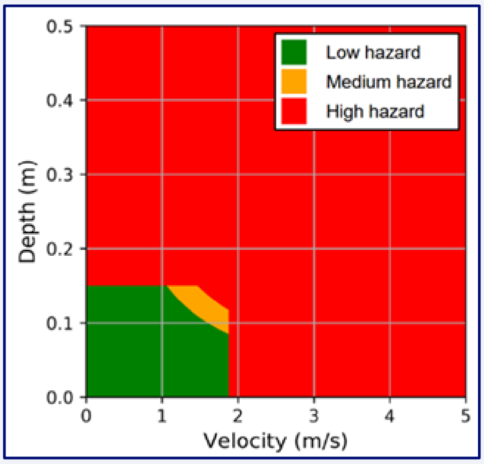


The figure below offers a general view of the economic impact on properties for each municipality for two different T10 events (historic and long-term climate change projection). According to historic data, Barcelona is the only municipality where damages reach more than 20M € of damages. It's also visible how smaller municipalities are predicted to be less affected by pluvial floods. When comparing this historic rainfall patterns with the predictions for the 2071-2100 period, there is a clear increase of impact on most municipalities with three of them (Sant Cugat del Valles, Sant Boi de Llobregat and Montcada i Reixac) reaching the 20M € mark.



5.1.2 Risk assessment of pluvial floods on people

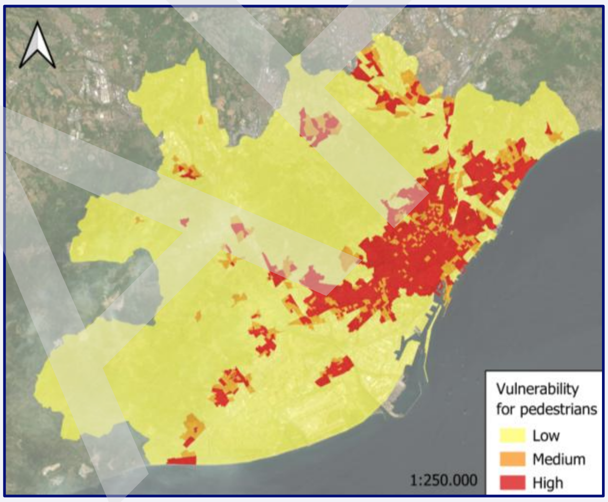
Risk assessment of PLUVIAL FLOODS on PEOPLE
Risk assessment methodology
The risk assessment of pluvial flood on people consisted of analyzing the impact of flooding on the surfaces of the 2D domain of the AMB particularly in regard to pedestrians, as they can be exposed to runoff that have the ability to cause falls and subsequent injuries and even fatalities.
Hazard assessment on PEOPLE
Flood criteria used for the hazard assessment on people is based on the combination between water depth and velocity obtained from the flood models. This data is analyzed to evaluate potential hazard on pedestrians categorized in three different categories (low, medium and high hazard). The flood hazard criteria, achieved by UPC through experimental and numerical campaigns were applied in several recent research projects like RESCCUE and BINGO (Martínez-Gomariz et al., 2016; Russo et al., 2013), and have been used also for the flood hazard assessment performed within ICARIA for the 36 municipalities of the AMB case study.



This information, crossed with exposure and vulnerability, results in the impact assessment of pluvial floods on people within the AMB.

Exposure and vulnerability assessment on PEOPLE

In the case of people, the assessment was designed as a combined calculation of vulnerability and exposure, as established by project CORFU and BINGO (Velasco et al., 2016). This methodology takes into account different characteristics of the AMB census areas such as the age of inhabitants, the percentage of foreign people and the urban density. Vulnerability level of the exposed subjects is considered as the average of these three indexes and categorized as low (1), medium (2) or high (2). Specific values for each level are reflected on the table below. The map presents a visual of the final vulnerability map on people.



Combined Exposure and Vulnerability index	Parameter C (5 of inhabitants with age < 15 or > 65 years)	Parameter F (% of foreign people)	Parameter D (urban density)
1 (low)	⩽ 33%	⩽ 33%	⩽ 10 houses/200m
2 (medium)	33% < X ⩽ 50%	33% < X ⩽ 50%	10 houses/200m < X ⩽ average local density
3 (high)	> 50%	> 50%	> average local density

Risk assessment results on PEOPLE

Risk for pedestrians (people) was calculated by overlapping hazard and vulnerability maps and applying the following matrix. The product of the hazard score (1 to 3) and the exposure and vulnerability index (1 to 3) result in a risk index (1 to 9). The risk for pedestrians at censal area levels is categorized between low and high according to the risk index (Matínez-Gomariz et al., 2019).

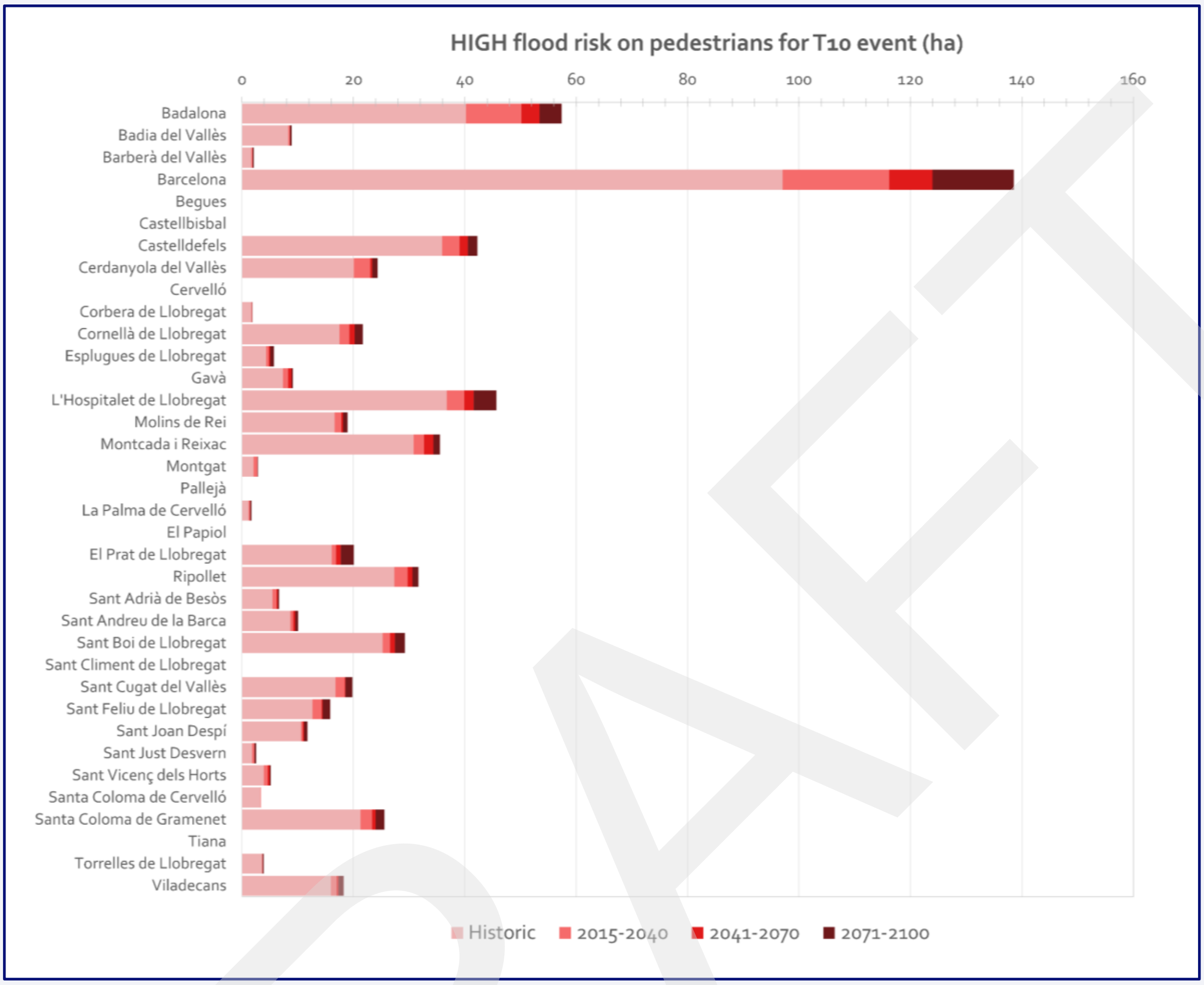
		Hazard		
		Low [1]	Medium [2]	High [3]
Vulnerability	Low [1]	1	2	3
	Medium [2]	2	4	6
	High [3]	3	6	9

The following table summarizes the total area classified as high risk for pedestrians for all the simulations considered. In addition, it indicates the percentual growth with respect to the high-risk area of the historic period for the corresponding return period.

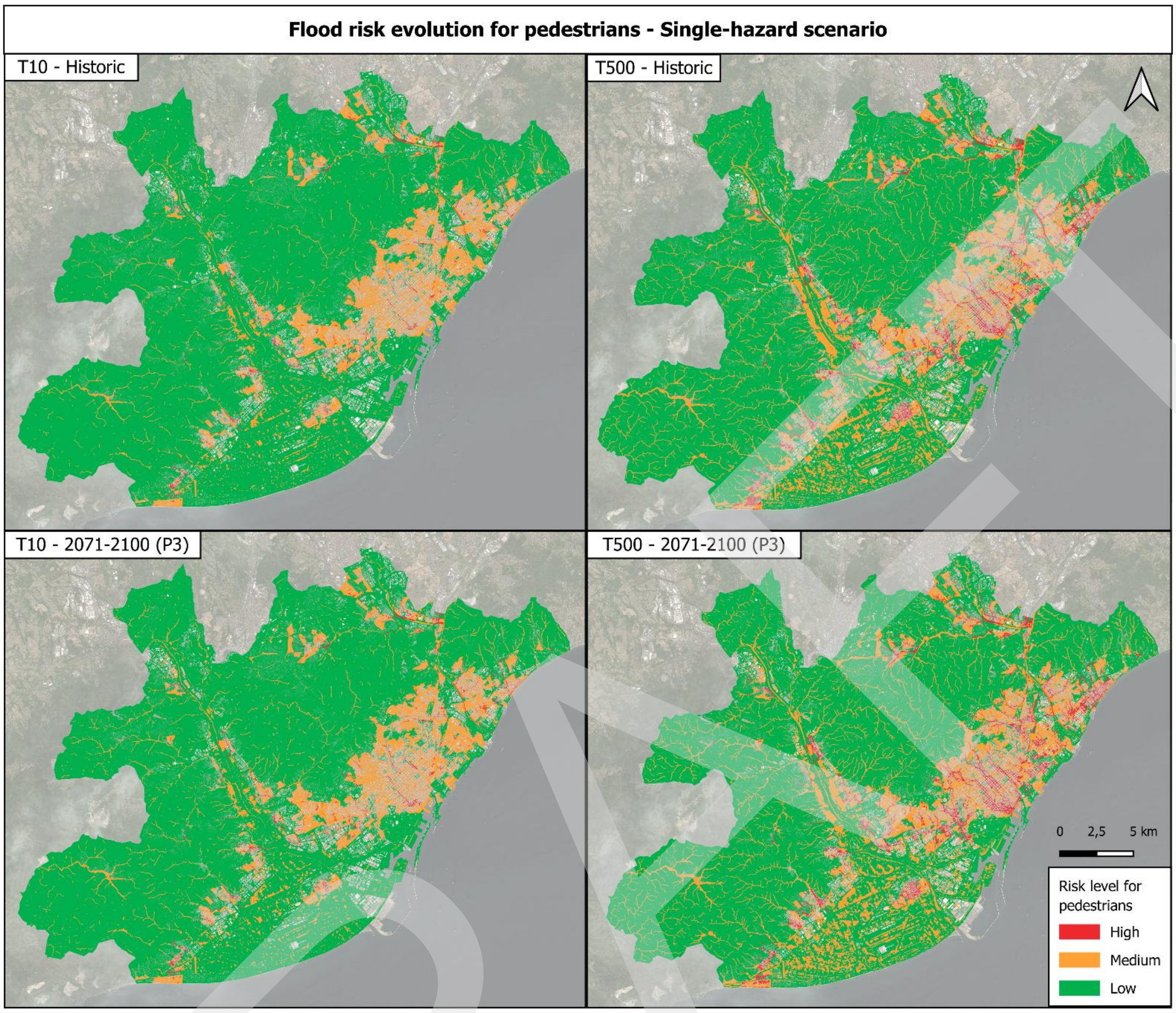
The results indicate a general increase in the extent of areas classified as high flood risk for pedestrians across future projection periods and return periods when compared to the historic scenario. For the more frequent events (T10 and T50), the high-risk area shows a progressive growth from the short-term projection to the end-century period, with increases becoming higher in 2071–2100. The T100 and T500 return periods exhibit a relatively moderate, but still significant, rise overall in comparison to T10 and T50. In absolute terms, the high-risk areas grow very significantly across return periods, always being T500 the most critical event in all projection periods.

	Area of HIGH flood risk on pedestrians for the return periods considered (ha) (and percentage of increase with respect to historic event)				
Projection Period	**T1**	**T10**	**T50**	**T100**	**T500**
Historic	0.00	494.14	918.68	1174.76	1818.69
2015-2040	19.42	554.06 (+12.1%)	987.67 (+7.5%)	1245.11 (+6.0%)	1856.01 (+2.1 %)
2041-2070	20.94	577.69 (+16.9%)	1007.35 (+9.7%)	1270.60 (+8.2%)	1879.70 (+3.4%)
2071-2100	31.54	620.75 (+25.6%)	1121.02 (+22.0%)	1400.63 (+19.2%)	1972.91 (+8.5%)

The following figure shows the total high-risk flood area for pedestrians for the T10 rain events across the four projection periods. When the total results are aggregated in municipalities, two main trends can be observed. Firstly, the larger the municipality, the larger the extent of the high-risk area. Secondly, the larger increases among projection periods are observed in the most densely urbanized municipalities (e.g. Barcelona, Badalona, Hospitalet, or Prat de Llobregat). This behavior is consistent with the fact that heavily urbanized areas have a higher runoff generation capacity in comparison with peri-urban areas, which generally surround the lower-density municipalities in the AMB.



Regarding the spatial distribution of medium and high-risk areas, the following maps depict their location of T10 (Historic and Period 3) and T500 (Historic and Period 3). Logically, they concentrate in the preferential water paths since these areas accumulate most of the runoff transportation. Most peri-urban streams are classified as medium-risk areas as they concentrate high water depths and velocities but are located in low to non-populated areas showing low exposure and vulnerability. On the contrary, high-risk areas are found in steep or low-lying urban areas. Despite accumulating less water than peri-urban streams, their location in densely populated areas raises the local vulnerability index. When comparing the same return periods in different climate change projections it can be seen that future high-risk areas tend to extend around the ones already identified for the historic scenario.



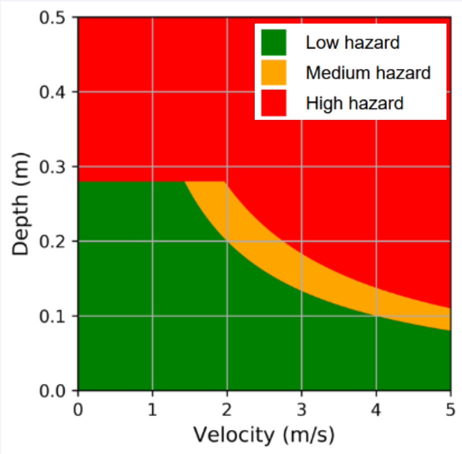
5.1.3 Risk assessment of pluvial floods on transport

Risk assessment of PLUVIAL FLOODS on TRANSPORT

Risk assessment methodology

Floods can directly affect traffic safety, vehicle stability and network performance. This part of the study is focused on establishing areas with a higher risk of loss of stability for vehicles due to pluvial floods. Also in this case, flood risk assessment is evaluated combining hazard and vulnerability components of the exposed vehicles.

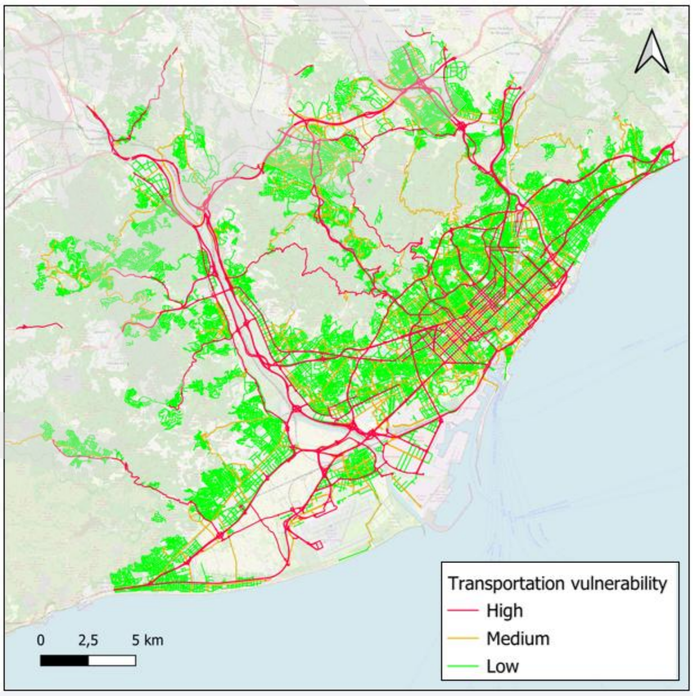
Hazard assessment on TRANSPORT



Flood hazard criteria applied to the assessment on transport were achieved by UPC through experimental and numerical campaigns (Martínez-Gomariz et al., 2017) and applied in recent projects like BINGO and RESCCUE (Eduardo Martínez-Gomariz et al., 2019; Russo et al., 2020). These hazard criteria can be expressed as a combination between flow depth and velocity and express the possibility of a vehicle to lose its stability due to buoyancy or dragging phenomena. For this analysis, a Seat Ibiza vehicle (see vulnerability section) was selected. The Seat Ibiza model stability threshold is (vy) = 0.40 m2s for dragging and presents a buoyancy depth of 28 cm. Also in this case, flood hazard can be categorized as either low, medium or high.

Exposure assessment on TRANSPORT

The exposure analysis of transport considered the whole driven transportation network of the AMB, including all streets, road and highways. The exposure of each section was defined based on its importance category, as it is defined in OpenStreet maps. According to this, all highways, roads, primary and secondary links were classified as "high" vulnerability, tertiary links as "medium" vulnerability, and "residential streets as "low" vulnerability. Other studies could adjust this classification with vehicular intensity data of the area of study. However, this information was not homogeneously available in the AMB. Furthermore, this classification is consistent with the expected traffic intensity in links according to their relevance.



Vulnerability assessment on TRANSPORT

In order to express the intrinsic characteristics of the risk receptor (vehicle in this case), a small-medium car typology (SEAT Ibiza) was considered for this analysis. This proposed vehicle for AMB is on the most best-selling vehicles in Spain and AMB and was chosen due its lowest stability according to the methodology proposed by (Martínez-Gomariz et al., 2017).

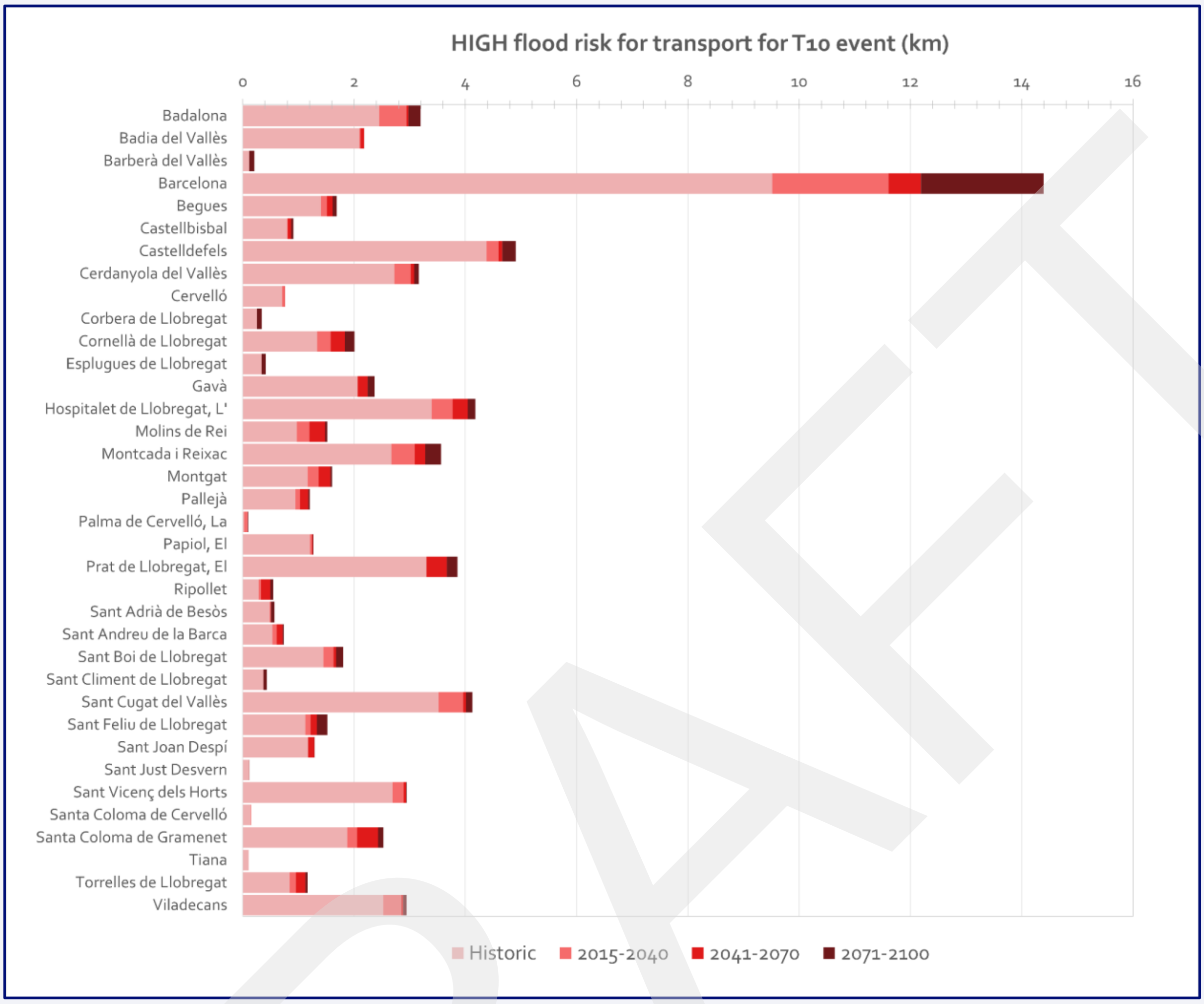
Risk assessment results on TRANSPORT

Risk for vehicles (transport) was calculated following the same principle as for pedestrians: overlapping hazard scores (1 to 3) and vulnerability maps (1 to 3) and applying the risk classification matrix (1 to 9). Next, each section of the road network is classified in low, medium and high risk.

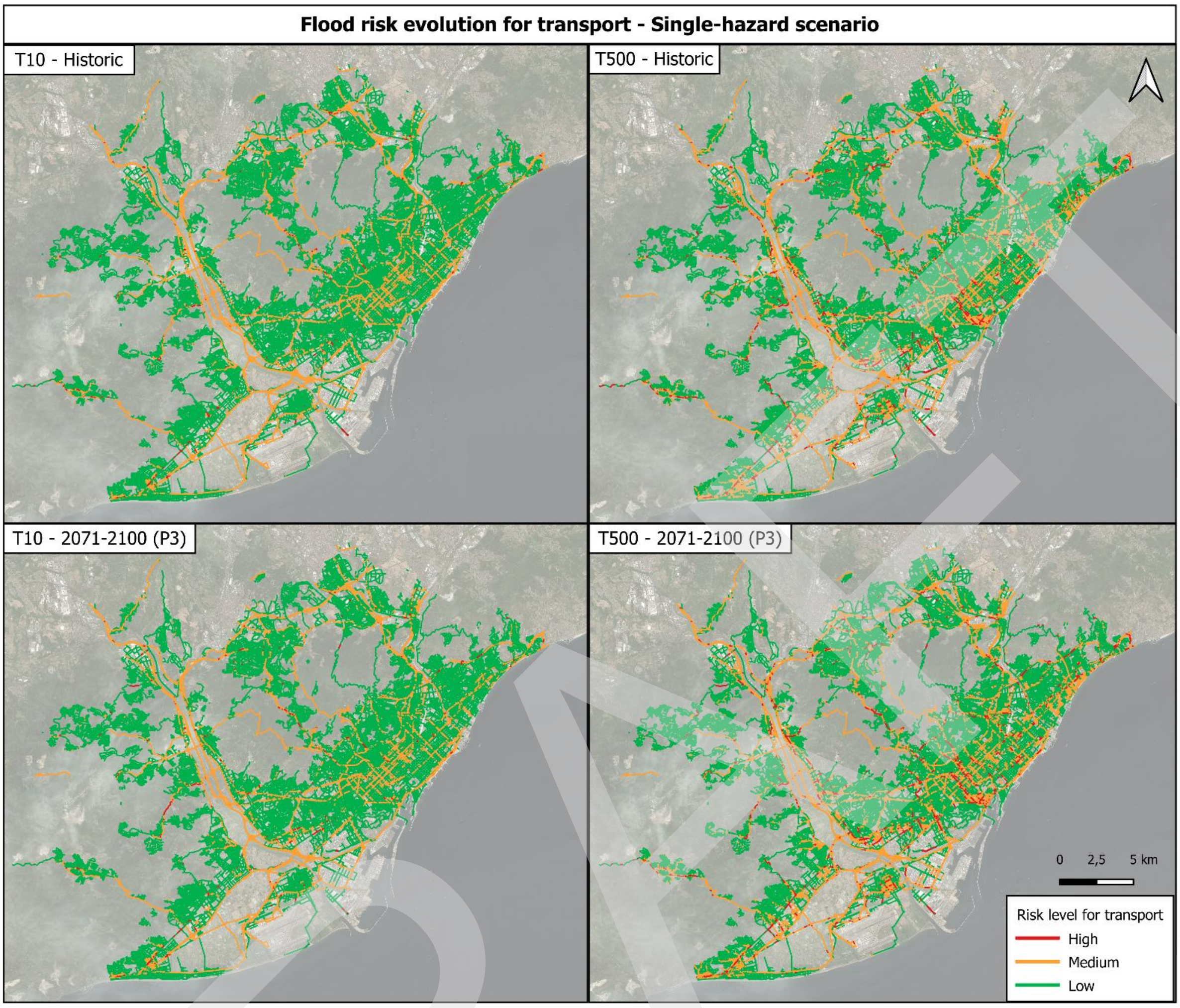
The total extent of the high-risk road network for all the return periods and climatic change scenarios considered is shown in the following table. Results show a similar trend to the high-risk area for pedestrians in the previous section. For all projection periods, the impacts of T1 events are close to null. The baseline (historic) simulation shows that up to 271.26 km can suffer high-risk conditions for a T500 event; this number could grow to 306 km by the end of the century. More frequent events, like T10 rainfalls, can impact 59 km of road according to the current rain patterns, increasing by 25% for projection period 3. The T50 and T100 events show similar behavior.

	Area of HIGH flood risk on transport for the return periods considered (km) (and percentage of increase with respect to historic event)				
Projection Period	**T1**	**T10**	**T50**	**T100**	**T500**
Historic	0.09	59.11	120.54	160.17	271.26
2015-2040	3.64	65.32 (+10.5%)	132.45 (+9.9%)	172.55 (+7.7%)	282.11 (+4.0 %)
2041-2070	3.66	69.37 (+17.4%)	135.54 (+12.4%)	175.47 (+9.6%)	287.24 (+5.9%)
2071-2100	5.01	74.37 (+25.8%)	151.54 (+25.7%)	198.88 (+24.2%)	306.55 (+13.0%)

Again, the municipalities concentrating more kilometers of streets and roads suffer larger impacts. In this sense, Barcelona leads the ranking. However, it can be observed that the extent of high-risk floods grows in all municipalities of the AMB as the effects of climate change become larger. In this sense, the risk associated with a specific return period under the current climatic conditions will grow significantly for the same return period in the future.



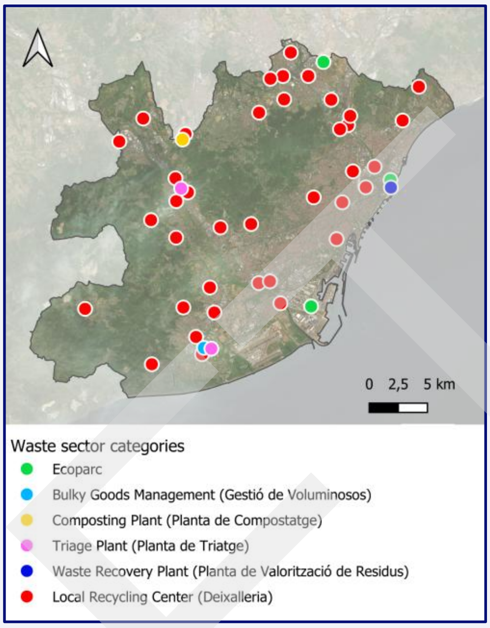
The following maps illustrate the spatial distribution of low, medium, and high-risk roads and streets for different return periods and climate projection periods. Most highways and interurban roads are classified as medium-risk areas for all. These infrastructures are built in accordance with risk-protection guidelines that help prevent flooding to some extent. However, their high traffic intensity makes them particularly vulnerable parts of the transport network. Some parts located in flood-prone areas even show high-risk conditions for T10 events. Within coastal cities like Barcelona and Badalona, an important number of streets present medium and high-risk conditions. These areas concentrate large flood-prone urban areas and high traffic intensity links, resulting in extensive areas with risk of car dragging and buoyancy due to water accumulation.



5.1.4 Risk assessment of pluvial floods on waste sector

Risk assessment of PLUVIAL FLOODS on WASTE SECTOR
Risk assessment methodology
There is a special interest among the local stakeholders of the AMB CS to study the impact of different climate hazards on critical infrastructure and assets. This part of the study focuses on how pluvial floods of different return periods can affect the waste management sector within the AMB. This analysis is based on the location of the most important infrastructure for waste management located in the AMB and the direct economic damage suffered for different flood scenarios.
Exposure assessment on WASTE SECTOR
In collaboration with the AMB administration and main operators of waste management, relevant stations for waste collection and treatment throughout all the studied area were selected. This

selection was based on relevance of the provided service and location. The buildings studied were categorized depending on their role within waste management. The analysis was finally applied to a total of 46 infrastructures which include 38 Local Recycling Centres, 3 Ecoparcs, 2 Triage Plants, 1 Composting Plant, 1 Bulky Good Management Plant and 1 Waste Recovery Plant. Each of these assets was then associated with its specific parcel.



Vulnerability assessment on WASTE SECTOR

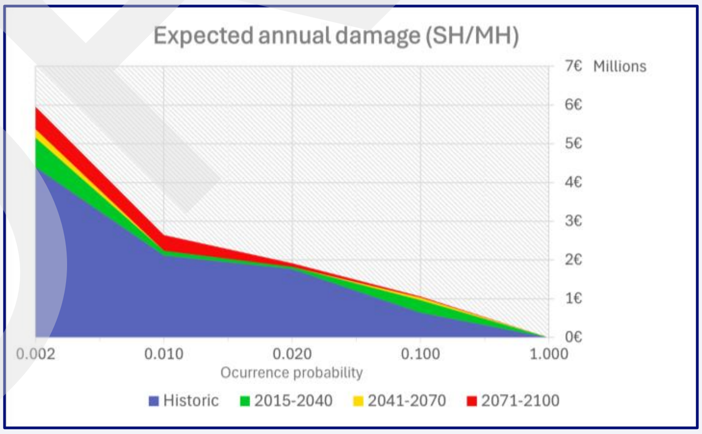
Vulnerability of waste assets was done through the same process as vulnerability of properties. Tailored depth-damage curves were used to identify economic impact of flood events for this kind of land use. For the waste management sector assets, differences of economic impact depended mostly on the type of building. Warehouses or local recycling centres will be less impacted by floods than big ecoparcs. These curves were then crossed to the flood depth within the building following the approach already used for properties of each scenario extracted from the modelled simulations.

Impact assessment results on WASTE SECTOR

The results of this impact assessment show that the waste sector can suffer critical damages for potential future flooding events above all in case of extreme rainfall events (from T10). Due to their locations, the simulated events will affect only local recycling centers, a composting plant and ecoparcs.

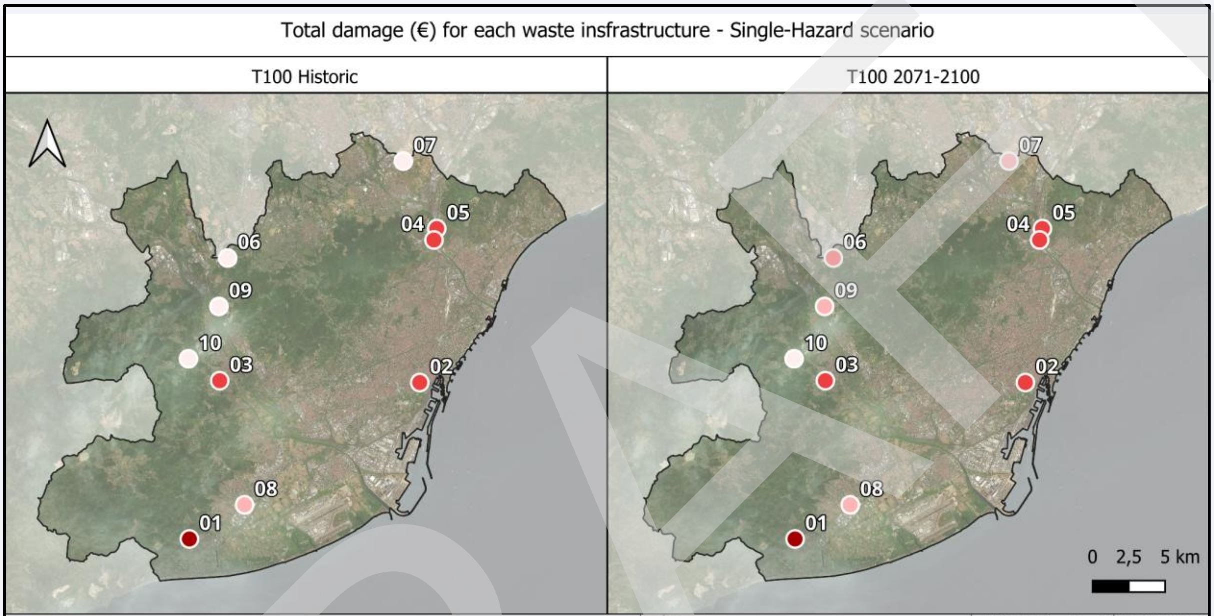
As the table below shows, local recycling centres present the bulk of monetary loss due to flood events. Ecoparcs and composting plants are only affected by T100 or T500 events. Local recycling plants can suffer more than 1M € in economic impact for a T10 event in the periods from 2041-2070 and 2071-2100; while Ecoparcs reach up to almost 50.000 € in losses and composting plants 260.000 € for the worst-case scenario (T500 event for the furthest future period). The estimated annual damage on local recycling plants increases by more than 50% compared to historic data for the period of 2071-2100 and so does the total damage to the waste sector.

	Economic damage on waste sector for the return periods considered (and percentage of increase with respect to historic event)					
Projection Period	**T1**	**T10**	**T50**	**T100**	**T500**	**Expected annual damage**
Local recycling centre (Deixalleria)						
Historic	0 €	643.516 €	1.771.288 €	2.118.686 €	4.085.352 €	430.440 €
2015-2040	0 €	962.857 €	1.827.705 €	2.236.799 €	4.893.013 €	593.750 € (+37,9%)
2041-2070	0 €	1.025.979 €	1.827.705 €	2.239.844 €	5.068.383 €	625.409 € (+45,3%)
2070-2100	0 €	1.053.728 €	1.916.620 €	2.507.644 €	5.646.892 €	647.731 € (+50,5%)
Ecoparcs						
Historic	0 €	0 €	0 €	0 €	48.827 €	195 €
2015-2040	0 €	0 €	0 €	2.081 €	48.827 €	214 € (+9,6%)
2041-2070	0 €	0 €	0 €	2.081 €	48.827 €	214 € (+9,6%)
2070-2100	0 €	0 €	0 €	48.827 €	48.827 €	635 € (+225,0%)
Composting Plant (Planta de compostatge)						
Historic	0 €	0 €	0 €	0 €	260.580 €	1,042 €
2015-2040	0 €	0 €	0 €	0 €	216.077 €	864 € (-17,1%)
2041-2070	0 €	0 €	0 €	0 €	260.580 €	1.042 € (+0,0%)
2070-2100	0 €	0 €	0 €	86.967 €	260.580 €	1.185 € (+75,1%)
Total waste sector						
Historic	0 €	643.516 €	1.771.288 €	2.118.686 €	4.394.759 €	431.678 €
2015-2040	0 €	962.857 €	1.827.705 €	2.238.880 €	5.157.917 €	594.828 € (+37,8%)
2041-2070	0 €	1.025.979 €	1.827.705 €	2.241.926 €	5.377.790 €	626.665 € (+45,2%)
2070-2100	0 €	1.053.728 €	1.916.620 €	2.643.437 €	5.956.299 €	650.191 € (+50,6%)



The figure below shows the specific infrastructures that are affected for a T100, comparing the historic data with the period of 2071-2100. As reflected on the figure and mentioned earlier, local recycling centers are most affected by these flood events, especially the Deixalleria de Castelldefels (1.5M € for a T100 2071-2100).

Besides the economic damage assessed for assets of the waste sector in the AMB. It should be noted that most of them correspond to local recycling centers (deixalleries). They are not truly industrial waste management sites that severely affect the waste management cycle in this region. Therefore, the largest operational risk corresponds to Ecoparc 2 (in Montcada i Reixac) and the composting plant of Sant Cugat.



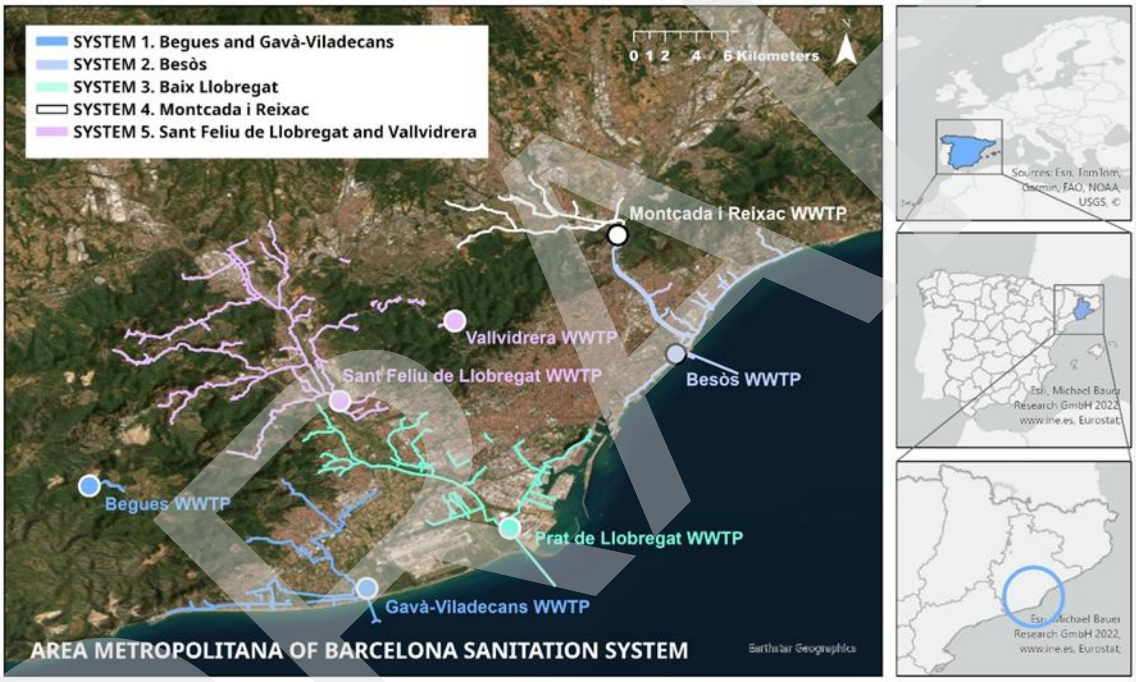
id	Name	T100 Historic - €	T100 P3 - €
01	Deixalleria de Castelldefels	1215601	1472063
02	Punt Verd barri Folch i Torres	440161	454155
03	Deixalleria de Sant Vicenç dels Horts	200277	280725
04	Punt Verd zona Vallbona	106127	134427
05	Deixalleria de Santa Coloma de Gramenet	107955	114995
06	Planta de compostatge de Sant Cugat	0	86967
07	Ecoparc 2 Montcada i Reixac	0	48827
08	Deixalleria de Viladecans	33627	33627
09	Deixalleria del Papiol	8486	10764
10	Deixalleria de Cervelló	6452	6888

5.1.5 Risk assessment of pluvial floods on water sector (WWTP)

Risk assessment of PLUVIAL FLOODS on WASTEWATER TREATMENT PLANTS

Risk assessment methodology

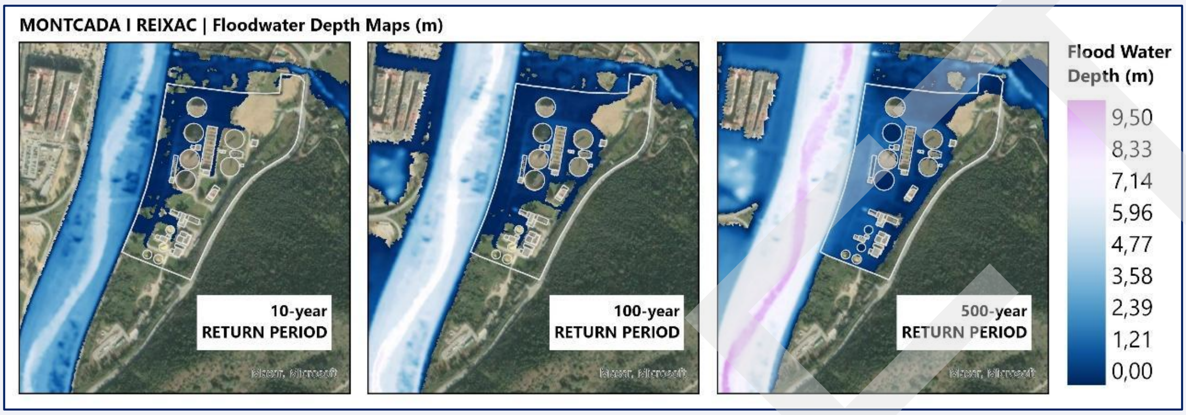
This research evaluates the potential direct and tangible flood damage to wastewater treatment plants (WWTP) within the Metropolitan Area of Barcelona (AMB) wastewater facilities, as shown in the figure. The risk framework combines hazard, exposure, and vulnerability components to estimate expected economic losses. Specific hydrodynamic simulations using IBER tool were performed for different return periods, and the resulting water depths were spatially integrated with WWTP layouts to quantify physical damages using depth-damage functions derived from empirical data and specifically developed for this type of wastewater infrastructure (Flor Tey et al., 2025)).



Hazard assessment of WASTEWATER TREATMENT PLANTS

Flood hazard and exposure were characterized through a bidimensional hydrodynamic modelling using Iber software, applied to 6 domains potentially affecting the Metropolitan Area WWTPs. For each domain, different water sources (rivers and ephemeral streams) were incorporated, with flow rates corresponding to the 10-, 100-, and 500-year return period IDF curves. A 2x2 m high-resolution DEM was used and further refined by including specific buildings, walls and equipment, and culverts within the WWTP areas and along the main watercourses.
Due to the large surface and structural complexity of the WWTPs, each facility was subdivided into several functional zones to allow a detailed spatial analysis of flood impact. This subdivision considered the layout of operational units (e.g., pretreatment, biological reactors, sludge lines, pumping and electrical buildings) and their elevation. For each subdivision, two indicators were extracted from the flood model outputs: flooded area percentage and average water height (m). A total of 18 flood scenarios (6 domains × 3 return periods) were simulated. The results indicate that

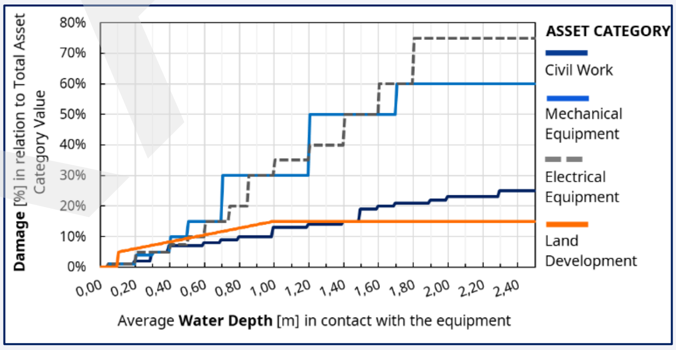
only a few WWTPs are significantly affected: Montcada i Reixac and Vallvidrera are the most exposed, while Gavà–Viladecans, Begues, and Sant Feliu de Llobregat show limited inundation, and Baix Llobregat remains unaffected in all simulations.
An example of the map showing the maximum water depths at the Montcada i Reixac WWTP for different return period events is presented in the figure.



Vulnerability assessment of the exposed WASTEWATER TREATMENT PLANTS

Vulnerability was characterized using new and innovative depth–damage curves developed from scratch for wastewater treatment plants based on the expertise of an experimented flood surveyor in sanitation system. The curves express the expected percentage of damage as a function of flood depth, distinguishing four asset categories: Civil works, mechanical equipment, electrical equipment, and land development

Before applying these functions, each subdivision within the WWTPs was economically valued according to its asset category and typology, construction characteristics, and the type of equipment it contains. The valuation was based on as built construction projects provided by Aigües de Barcelona and standard unit values (€) for wastewater facilities. This allowed the economic significance of each zone to be reflected accurately in the total loss estimation.

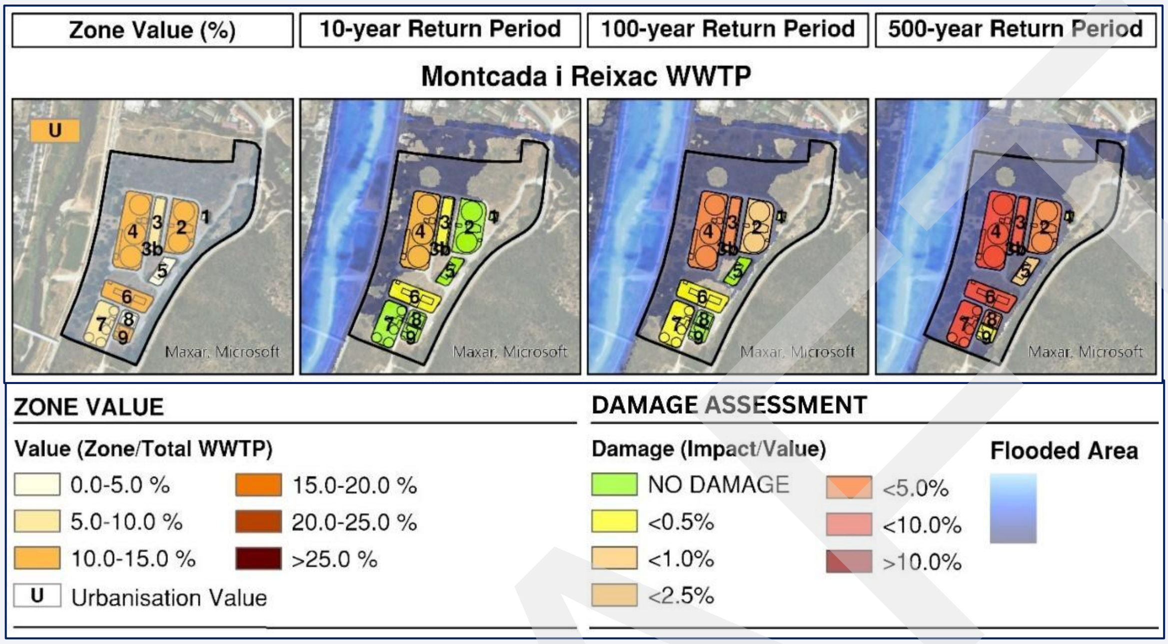


For indoor components, permeability coefficients were used to link external and internal flood depths, while open-air structures (e.g., clarifiers) were considered affected only when flood depth exceeded their perimeter wall height. The maximum damage ratio established around 1.8 m depth, reaching up to 75% for electrical assets.

Impact assessment results

Flood damage was calculated for each subdivision and asset category by multiplying the damage ratio (from the vulnerability curves) by its economic value, yielding the direct economic loss per zone. These were then aggregated to obtain total damages at the plant and regional scale. Impact assessment framework is illustrated in the figure.

The results include damage maps expressed as a percentage of the total asset value for each section within every facility, as illustrated below for the Montcada i Reixac WWTP.



The findings show that Montcada i Reixac is the most affected plant, with estimated physical damages of 2% and 6% for the 100- and 500-year return period events, respectively. In monetary terms, this corresponds to approximately €1 million and €3.5 million. The remaining facilities present impacts below 1% of their total asset value, mainly caused by the overflow of nearby ephemeral streams or irrigation channels.

Across all facilities, civil works account for most total losses, representing approximately 87% of the total damage. The contribution of mechanical and electrical components increases with flood depth, reaching between 28% and 50% of total damages in the most severe events (in Vallvidrera, for the 500-year return period event). The most affected areas within the WWTPs correspond to those containing the highest-value equipment, such as the biological reactor, the tertiary treatment, and the sludge line, where a combination of structural exposure and sensitive assets amplifies potential losses. Conversely, pretreatment units and settling tanks show comparatively lower damage ratios, reflecting both their simpler construction and lower replacement costs.

The validation process confirmed the robustness of the methodology: simulated results were compared with historical flood loss data from the Spanish Insurance Compensation Consortium (CCS), showing good agreement with observed ranges for similar facilities across Spain, excluding events recorded in low-capacity plants (<5000 pe). Of the 144 flood events recorded in wastewater treatment plants across Spain over the past two decades, only one case exhibited an average depth–damage ratio exceeding 6%, a result consistent with the order of magnitude obtained in the present case study. This cross-validation ensures the reliability of the estimated damages and supports the applicability of the model to other wastewater infrastructures.

Overall, the analysis highlights that even moderate floods can cause significant losses to key treatment facilities. These findings underscore the importance of incorporating flood resilience and asset prioritization into wastewater management and regional planning. Further information about this specific analysis can be found in Flor Tey et al., 2025.

5.1.6 Risk assessment of coastal floods on coastal areas

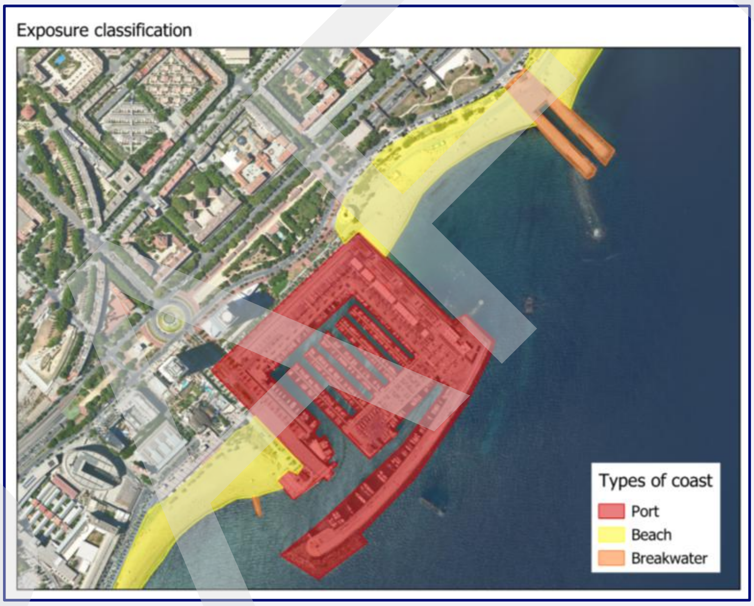
Risk assessment of COASTAL FLOODS on COASTAL AREAS

Risk assessment methodology

The risk assessment of coastal floods on coastal areas is focused on assessing the potential loss of assets in the shoreline due to the effect of mean sea level rise. This corresponds to the first approach described in section 4.3.1.2.

Exposure assessment on COASTAL AREAS

As explained in chapter 4, the Hazard for coastal floods is characterized through a simplistic hydrostatic approach considering the means sea level rise (approach one for coastal flood risk assessment). The model uses a high-resolution Digital Terrain Model (DTM) of all the coastline of the Barcelona Metropolitan Area (AMB). Exposure is characterized by dividing the coastline in three different categories (Beach, Port and Breakwater) depending on the main land use of the area. Analysis is conducted for these three types of area. The figure below shows the classification of exposure areas.



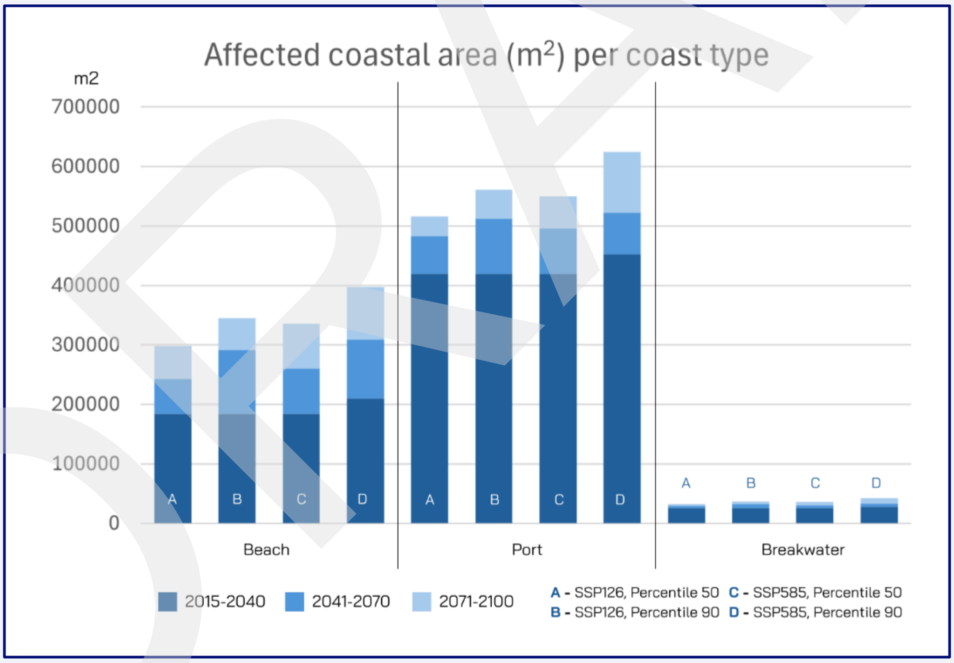
Two climate scenarios are considered (SSP126, and SSP585) for three projection periods (2015–2040, 2041–2070, and 2071–2100). For each scenario, the 50th and 90th percentiles of mean sea level rise were analyzed.

Impact assessment results

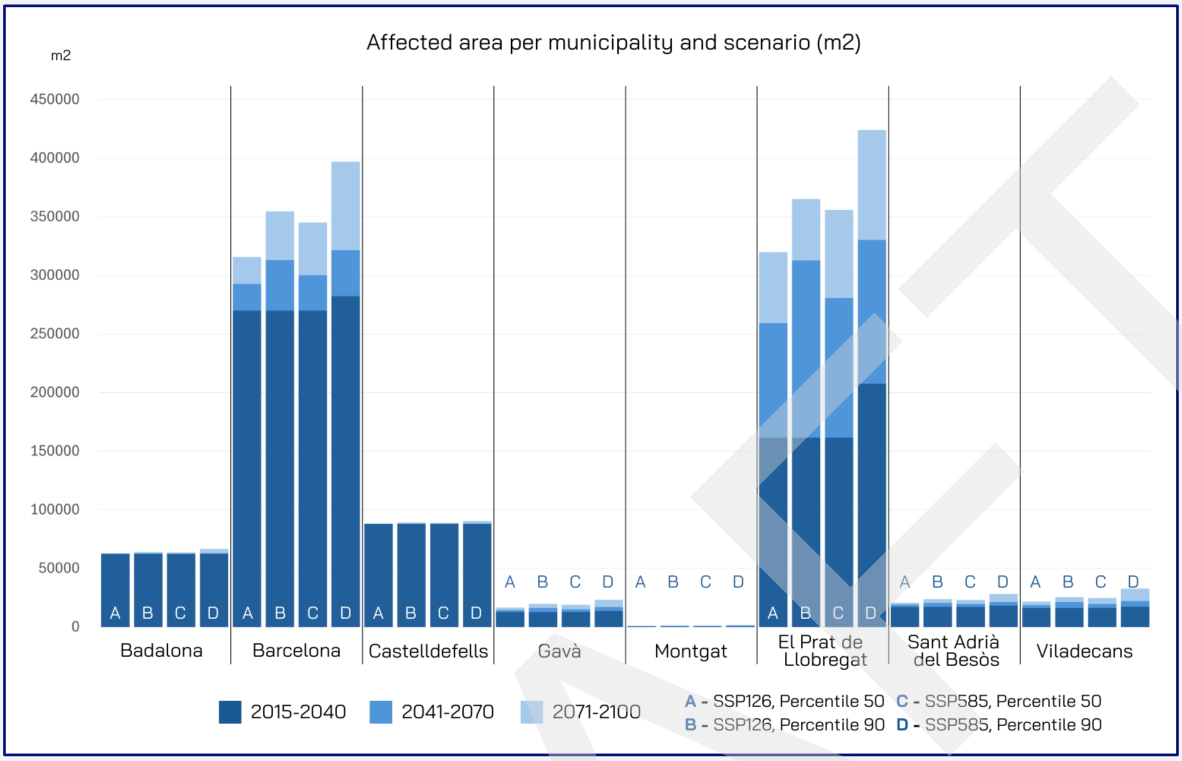
The following table summarizes the mean sea level rise associated with each climate change scenario. The hazard assessment results assume that the rise is homogeneous along the whole coast of the AMB. Results show the mean sea level rises for all scenarios considered together with the total area that would be affected by this hazard. The raise is particularly high for the last simulation period for all SSPs, and percentiles considered. When considering 90 percentile, mean sea level increases by 40% compared to the general results from percentile 50. From the most optimistic scenario to the most pessimistic, sea level rises almost half a meter more. This gives a general perspective of possibilities in the future.

SSP	Event intensity percentile	Projection period	Mean sea level rise (m)	Affected coastal area (m2)
126	50	2015-2040	0.12	628,821
		2041-2070	0.27	755,855
		2071-2100	0.45	846,598
	90	2015-2040	0.19	628,821
		2041-2070	0.44	835,980
		2071-2100	0.72	943,172
585	50	2015-2040	0.16	628,821
		2041-2070	0.33	786,845
		2071-2100	0.65	921,264
	90	2015-2040	0.19	690,460
		2041-2070	0.50	864,562
		2071-2100	0.99	1,063,856

The following graphs represent the affected area per type and per each of the scenarios simulated. They are a reflection of the combination of the mean sea level rise maps and exposure maps. It is clear through all scenarios that ports are the most exposed and affected areas throughout the AMB. Breakwaters, on the other hand, will lose less land to sea level rise. This may be explained simply by the difference in total area of ports, beaches and breakwaters. But also, as part of breakwaters nature itself, height of these infrastructures works as a barrier for increasing sea level.



As reflected in the figure below, the effect of this hazard won't be homogeneous among the coastal municipalities of the AMB. According to all simulated scenarios, the most affected cases are El Prat de Llobregat and Barcelona, which could lose, respectively, up to 0.42 and 0.40 square kilometers by the end of the century, according to SSP 585. The more optimistic SSP estimates that the loss can be limited to 0.37 and 0.35 square kilometers in each case.
Differences between municipalities are typically caused by topography and presence of existing seawater defenses which contribute to the mitigation of land loss to the sea.



5.1.7 Risk assessment of coastal floods on water sector (coastal main sewer)

Risk assessment of COASTAL FLOODS on COASTAL MAIN SEWER

Risk assessment methodology

The Llevant Main Sewer, a 10.8 km coastal-parallel infrastructure serving five municipalities of the Metropolitan Area of Barcelona, is particularly exposed to storm surge and sea level rise. The risk assessment combines hazard (considering the second approach described in section 4.3.1.2 considering extreme sea level and wave propagation), exposure, and vulnerability analyses to estimate potential economic impacts. Furthermore, in case of structural damage, an important environmental impact also exists due to wastewater and stormwater overflow into the receiving water body. Future wave and sea level projections from CMIP6 (SSP126 to SSP585) were downscaled from the Barcelona Buoy II and propagated toward shoreline using a linear wave model.

Exposure assessment of COASTAL MAIN SEWER

Exposure was characterized through the developed Protection Level Index (PLI), which classifies each section of the sewer according to its degree of physical protection against coastal hazards.

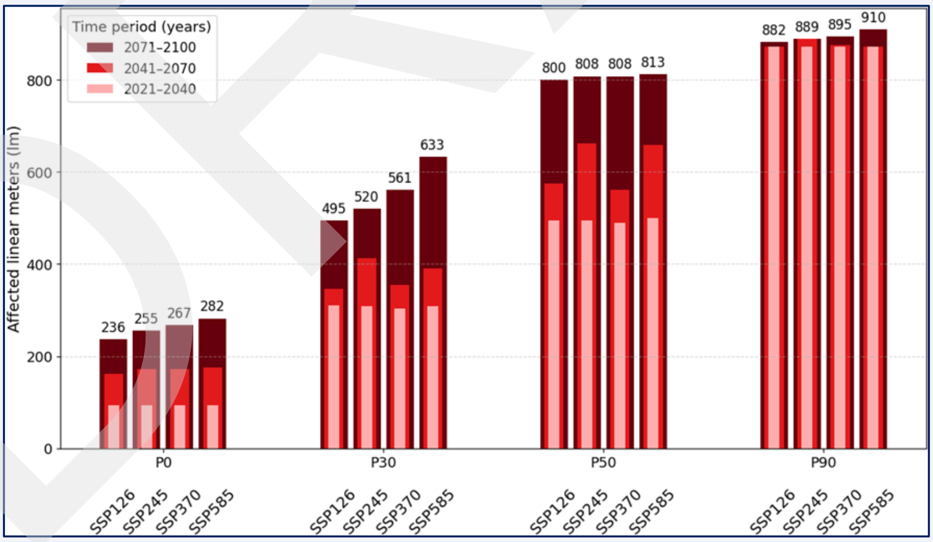
Five levels were defined, from PLI Lv.0 (fully exposed) to PLI Lv.4 (fully protected), based on field inspections and aerial imagery.

The combined water level affecting the infrastructure was expressed as the Event Extreme Sea Level (EESL), defined as the sum of the breaking wave height (Hb), obtained through linear wave propagation from offshore buoy data, and the projected mean sea level rise (SLR). This indicator represents the maximum hydrostatic load expected at the coastline for each scenario and time horizon.

Due to the relevance and the vulnerability of this key infrastructures, four climate scenarios were considered (SSP126, SSP245, SSP370, and SSP585) for three projection periods (2021–2040, 2041–2070, and 2071–2100). For each scenario, the 0th, 30th, 50th, and 90th percentiles of significant wave height were analyzed to represent increasing storm intensities. The 0th percentile, corresponding to a wave height of 2 m, was included because such events already cause measurable damage along the Catalan coast and are therefore considered relevant for impact assessment.

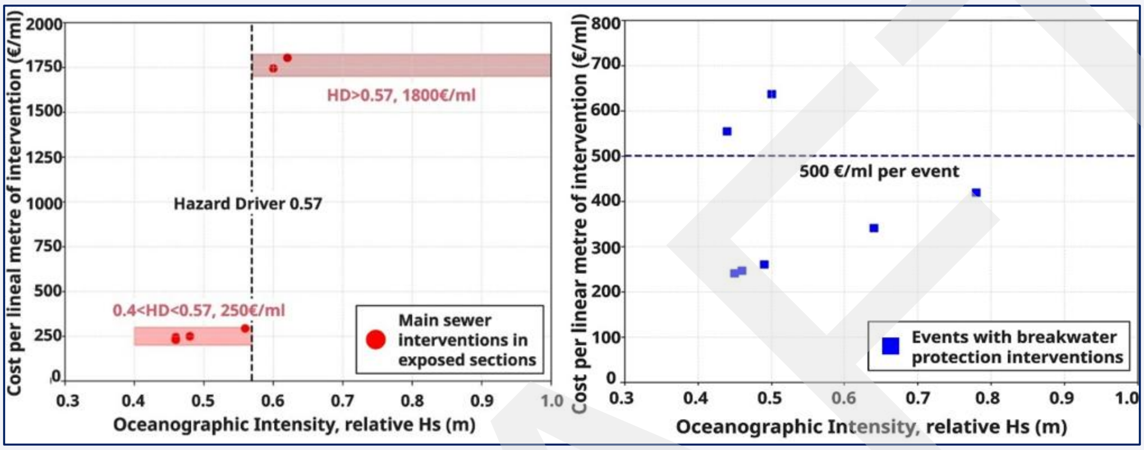
The affected linear meters are represented for the most favorable scenario (EESL = 2.41 m, corresponding to the 0th percentile under SSP126 for 2021–2040) and the most unfavorable scenario (EESL = 5.16 m, corresponding to the 90th percentile under SSP585 for 2071–2100).

The exposure analysis shows a clear temporal increase in the length and number of sewer sections affected by coastal flooding. As sea level rise progressively combines with storm surge effects, areas that are currently protected or only marginally exposed become increasingly vulnerable. By the end of the century, new exposed stretches appear (near Badalona Port), particularly under the high-emission scenario (SSP585), where elevated Extreme Event Sea Levels (EESL) reach previously unaffected zones. An example is shown illustrating the evolution of the exposed linear meters of the Unprotected Sections across the different scenarios and time periods.



Vulnerability assessment of COASTAL MAIN SEWER

Vulnerability functions were developed from historical repair data (Aigües de Barcelona 2017-2023) correlated with storm events recorded at Barcelona Buoy II. The hazard driver (**φ**) was defined as the ratio between event wave height (Hs EVENT) and the maximum historical wave height in the buoy (5.48m). To align with available repair data, exposure levels were grouped into **Unprotected Sections** (PLI Lv. 0.1) **and Rock Revetment-protected Sections** (PLI Lv. 2-3). The relationship between the hazard driver (**φ**) and the repair cost per linear meter (€/ml) was then defined.



Impact assessment results

The economic impact is defined as the potential financial losses resulting from the effects of sea level rise (SLR) and storm surges on the Llevant Main Sewer. Three management strategies were compared through a **cost-benefit analysis (CBA)** under the four SSP climate scenarios. The reference option, or **Business-As-Usual (BAU)** scenario, assumes reactive repairs carried out only after damage occurs. For these interventions, the repair cost was defined as 250€/m for moderate impacts (**φ** <0.57) and 1800€/m for severe impacts (**φ** >0.57), according to the vulnerability assessment.

Two **adaptation measures (AM)** were evaluated against this baseline. The costs (€/ml) associated with their implementation were derived from a specific alternatives study previously requested for this infrastructure:

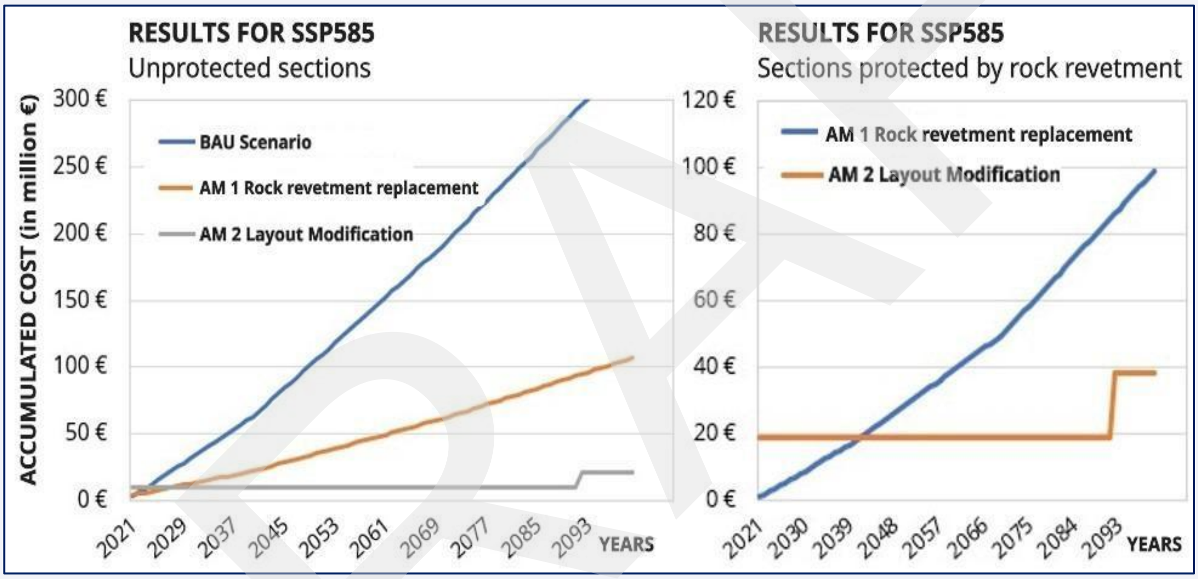
- **AM 1. Rock revetment protection.** Initial cost of 3700€/ml and an additional 500 €/ml for maintenance or replacement after each damaging event.
- **AM 2. Layout modification.** Relocating or elevating the infrastructure to avoid direct coastal exposure. This measure has an estimated cost of 11600€/ml and a project service life of 70 years, meaning full replacement would be required twice during the 2021-2100 period.

The economic analysis integrates hazard, exposure, and vulnerability results to estimate total costs under each climate scenario. For every percentile (0th, 30th, 50th, and 90th) and period, the number of storms events, affected length, and cost per meter were combined to compute cumulative damages. This method allows a consistent comparison between BAU and the adaptation strategies, identifying the most cost-effective alternative over time and across emission scenarios. Hence, the cost for a given period and climate scenario has been computed as it follows:

$$Cost = \sum_{i=1}^{4} (NºEvents \times Affected\ lm \times \frac{€}{lm})$$

Where each term of the summation corresponds to one of the four percentiles considered. The results reveal a clear increase in economic risk over time and across emission scenarios. Although the projected wave heights show limited variation between SSPs, the rise in mean sea level significantly amplifies the extent of exposed infrastructure. Consequently, the cumulative repair costs under the **Business-As-Usual (BAU)** approach for **unprotected sections** grow steadily, reaching between **290 and 335 million euros** by 2100, depending on the scenario. The most adverse conditions are observed under SSP585, driven by both higher event frequency and greater flooding depth.

The **Cost–Benefit Analysis (CBA)** demonstrates that both adaptation strategies significantly reduce long-term costs. For fully unprotected sections, implementing **rock revetment protection (AM1)** decreases cumulative losses by around **68%** compared to BAU, while **layout modification (AM2)** provides the greatest economic advantage, achieving savings of up to **94%**. In unprotected sections, AM2 becomes more cost-effective than BAU after only four to nine years, whereas in already protected sections the economic crossover occurs after roughly two decades. For **sections already protected by rock revetment**, AM2 also becomes the most efficient alternative in the long term, surpassing the repeated replacement strategy of AM1 after roughly **23 years**. The SSP585 scenario is shown in the figure as an example.



Across all SSPs, the relative differences between low- and medium-emission scenarios (**SSP126–SSP370**) remain moderate, whereas **SSP585** stands out as the most unfavorable, with total costs about **13–14% higher**. The results highlight the importance of proactive adaptation over reactive maintenance, showing that relocation or elevation of the sewer alignment (AM2) ensures greater resilience and lower cumulative expenditure for both unprotected and previously protected sections by the end of the century.

5.1.8 Indirect economic damages of pluvial flood

Risk assessment of INDIRECT ECONOMIC DAMAGE of PLUVIAL FLOODS

Risk assessment methodology

This risk assessment aims to evaluate the indirect economic costs of pluvial floods in the Metropolitan Area of Barcelona (AMB). In addition to direct physical damages to exposed assets, flood events generate indirect economic losses, primarily through business interruption and cascading effects that materialize beyond the flooded asset itself, either in time or space (Thieken et al., 2008; Hammond et al., 2015). The assessment builds upon the direct flood damage assessment on properties. Indirect damages are estimated by applying relationships between direct and indirect damages derived from a combined input–output and econometric modelling framework, calibrated for the AMB using historical flood loss and economic data. The assessment follows methodology explained in Deliverable 3.1 and is produced for four time horizons (Historical, 2015-2040, 2041-2070, 2071-2100) and for five return periods T1, T10, T50, T100 and T500. In addition, Expected Annual Damage (EAD) is calculated for each time horizon.

Hazard assessment on INDIRECT ECONOMIC DAMAGES

The hazard information used for the assessment of indirect economic damages is derived from the pluvial flood direct damage assessment on properties. In that assessment, flood hazard is characterized through urban pluvial flooding modelling, providing flood depths associated with extreme rainfall events for different return periods and scenarios (Martínez-Gomariz et al., 2021). No dedicated hazard model is developed specifically for indirect economic damages. Instead, direct economic damages act as the hazard-driven economic shock, which subsequently propagates through the metropolitan economy and generates indirect losses (Hallegatte, 2008).

Exposure assessment on INDIRECT ECONOMIC DAMAGES

Exposure to indirect economic damages is represented by the economic structure of the Metropolitan Area of Barcelona, rather than by individual physical assets or spatial locations. Exposure is characterized through ten aggregated economic sectors, which capture the main productive and service activities potentially affected by flood-induced business interruption and cascading effects. The level of exposure is therefore implicitly captured by the magnitude of direct flood damages previously estimated and by the assumed economic structure of the AMB. This aggregated approach allows indirect damages to be assessed consistently at metropolitan scale, while remaining compatible with data availability and uncertainty constraints.

Vulnerability assessment on INDIRECT ECONOMIC DAMAGES

Vulnerability to indirect economic damages is characterized through an empirical relationship between direct and indirect flood damages, derived from a modelling framework that combines input–output analysis and econometric regression. The input–output model is used to capture inter-sectoral economic dependencies and to quantify how direct flood damages propagate through the metropolitan economy, while the resulting estimates are employed to calibrate an econometric model from which the average indirect-to-direct damage ratio and the sectoral allocation coefficients are derived. The resulting framework indicates that, in the AMB, indirect damages amount to 29% of direct damages meaning that for every unit of monetary direct damage, 0.29 units should be considered to account for indirect economic losses. This value is consistent with findings reported in the literature for urban flood events (Carrera et al., 2013; Hallegatte, 2008). Total indirect damages are distributed across the ten economic sectors using a set of sectoral allocation coefficients (σ), which reflect the relative sensitivity of each sector to flood-induced economic disruption. These coefficients are applied consistently across all time horizons and return periods, assuming a stable economic structure over the assessment horizon.

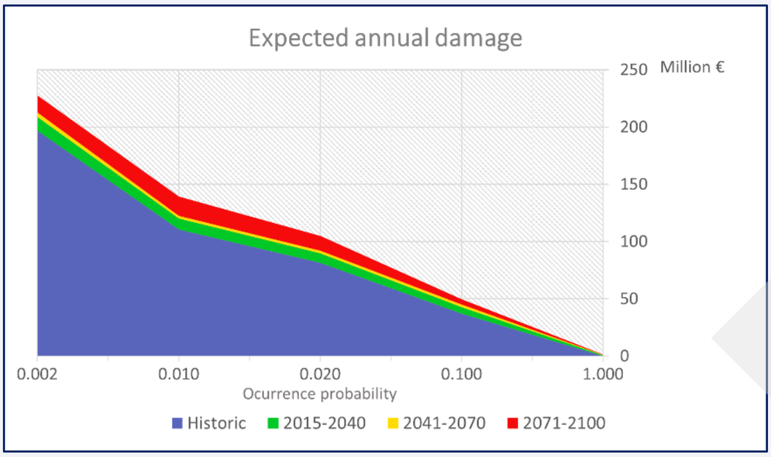
Economic Sector	Coefficient σ
Agriculture	0.0632
Industry	0.1857
Construction	0.1172
Retail	0.0634
Infor	0.1210
Finance	0.1735
Real estate	0.1196
Professional activities	0.1147
Public administration	0.0158
Arts & others	0.0254

Impact assessment results

The results indicate that indirect economic damages constitute a substantial component of total flood-related losses in the AMB and increase consistently with both flood severity and future time horizons. For the Historical period, total indirect damages range from approximately €36.9 million for T10 events to nearly €197 million for T500 events, with an Estimated Annual Damage (EAD) of around €23.5 million.

	Indirect Economic damage of pluvial floods (and percentage of increase with respect to previous event)					
Projection Period	**T1**	**T10**	**T50**	**T100**	**T500**	**Expected annual damage**
Historic	1.228,26	36.921.260,57	81.241.969,90	110.505.296,12	196.903.035,10	23.530.018,85
2015-2040	852.344,43	42.542.914,12 (+15,23%)	89.830.099,31 (+10,57%)	120.000.120,76 (+8,59%)	208.727.531,13 (+6,01%)	27.186.848,59 (+15,54%)
2041-2070	957.017,32	45.024.711,84 (+5,83%)	92.099.434,48 (+2,53%)	122.422.054,82 (+2,02%)	212.749.685,93 (+11,65%)	28.590.038,39 (+5,44%)
2071-2100	1.488.253,53	49.695.156,92 (+10,37%)	104.870.578,63 (+13,87%)	139.433.416,56 (+13,90%)	227.591.663,82 (+6,98%)	31.904.784 (+11,59%)

Future periods show a clear upward trend in indirect damages. For the 2015–2040 horizon, indirect damages reach approximately €42.5 million (T10) and €208.7 million (T500), with an EAD of about €27.2 million. This increasing pattern continues for 2041–2070, where total indirect damages exceed €45 million (T10) and €212.7 million (T500), and culminates in the 2070–2100 period, which represents the most adverse conditions. In this last horizon, indirect damages approach €50 million for T10 events and exceed €227 million for T500 events, with an EAD of approximately €31.9 million.



Overall, the evolution of EAD values from the Historical period to 2070–2100 reflects a progressive increase in long-term indirect flood risk, driven by higher direct damages and their propagation through the metropolitan economy.

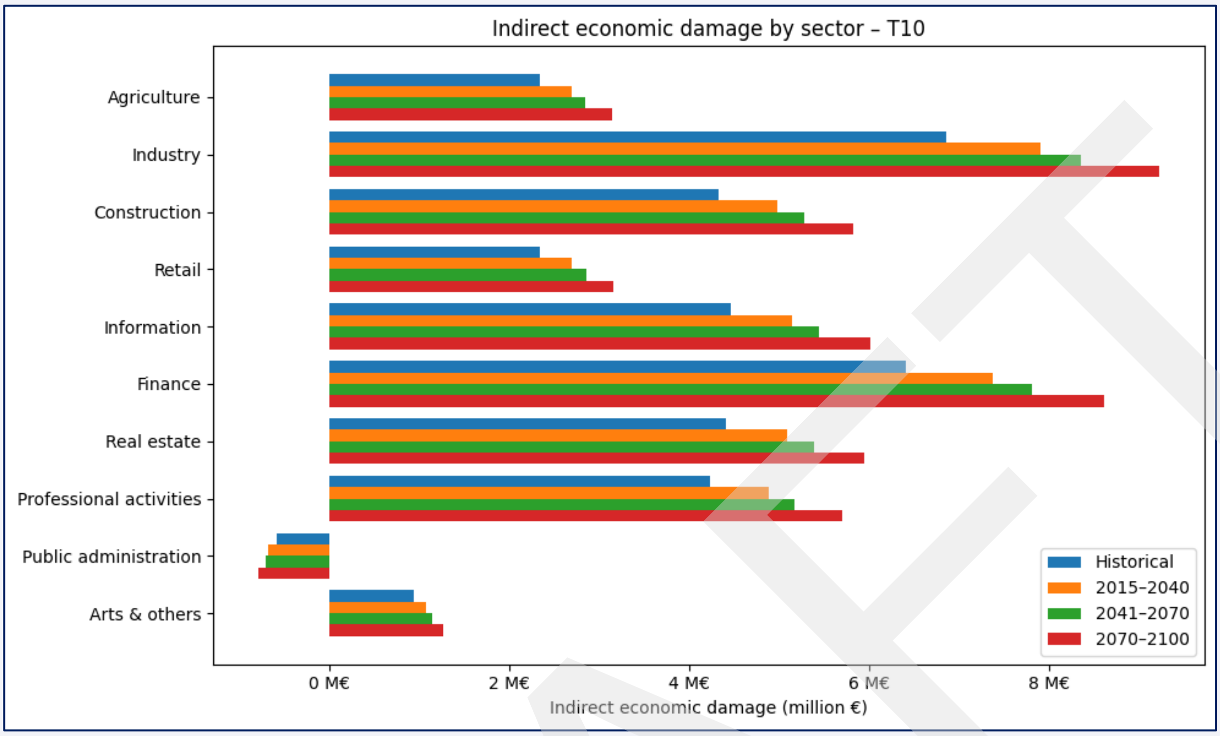
The sectoral breakdown highlights a non-uniform distribution of indirect economic impacts across activities. Across all time horizons and return periods, industry and financial activities consistently account for the largest share of indirect damages, together representing roughly 35–40% of total losses. For extreme events (T500) in the 2070–2100 period, indirect damages in these two sectors alone exceed €80 million, underlining their strong interdependencies and sensitivity to flood-induced disruptions.

A second group of highly affected sectors includes construction, real estate, professional activities, and information and communication services. Each of these sectors individually accounts for around 10–12% of total indirect damages. Their losses increase markedly with flood severity, reaching values between €24 million and €28 million for T500 events in the 2070–2100 horizon.

Agriculture and retail exhibit lower absolute indirect losses compared to other sectors, reflecting their smaller weight in the metropolitan economy. Nevertheless, indirect damages in these sectors are still significant, exceeding €13–14 million for extreme events in the later periods.

The public administration sector shows a negative contribution to indirect damages in all periods and return periods. This result originates from the econometric specification used to derive sectoral coefficients and should be interpreted cautiously. It does not imply actual economic gains, but rather reflects a comparatively lower sensitivity of public administration activities to business interruption effects within the adopted modelling framework.

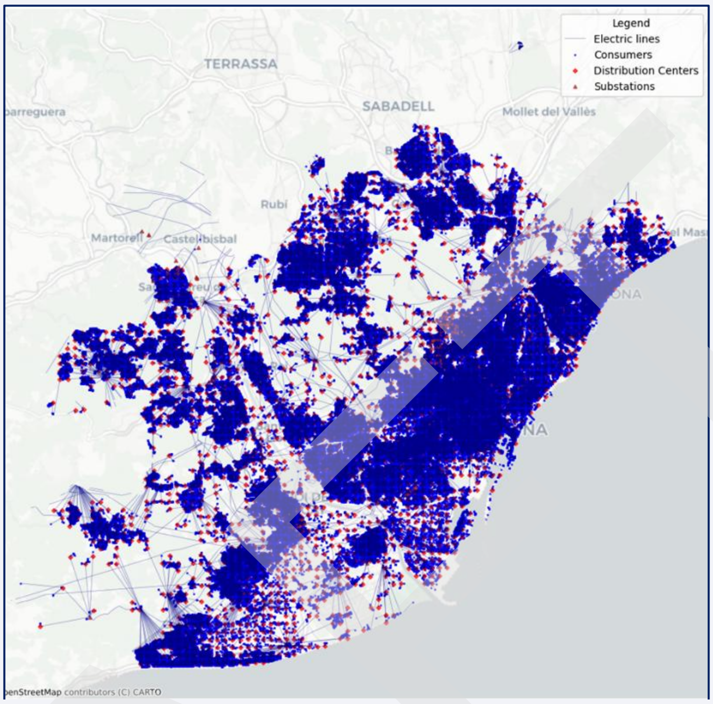
Finally, arts and other services represent a smaller but non-negligible share of indirect damages, with losses steadily increasing over time and reaching nearly €5.8 million for T500 events in the 2070–2100 period.



5.1.9 Risk assessment of pluvial floods on electricity

Risk assessment of PLUVIAL FLOODS on ELECTRICITY
Risk assessment methodology
The risk assessment of pluvial floods on the electricity aims to estimate the economic impact of this hazard on the electricity sector in the Metropolitan Area of Barcelona (AMB). This risk assessment evaluates the electrical assets' exposure and vulnerability and estimates the economic impact due to the hazard. This evaluation uses the pluvial flood scenarios calculated for the project to compare different cases and return periods, specifically for historical events with return periods of 1 to 500 years, SSP 585 with an extreme event with a percentile of 50%, and several projected periods from 2015 to 2100. This methodology is based on the methodology proposed by Sánchez-Muñoz et al., 2020.
Electrical network topology of ELECTRICITY
Due to the access data restrictions, some of the electrical network topology has been estimated. To create the network topology, open data and public information about electricity assets and consumers have been used. With the obtained information and using the knowledge of the zone, the electrical assets and its interactions have been estimated swooned on the following image.

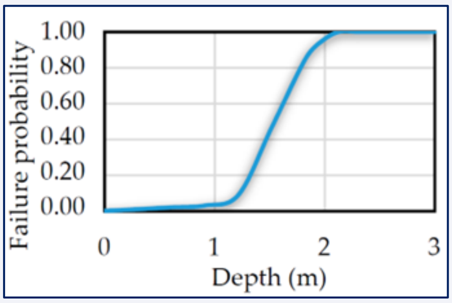
The previous image shows the electrical topology estimated for the AMB area. In total, there are 377 substations from 220 kV to 20kV, then 2254 distribution centers from 20kV to 230V, 295 High voltage electrical lines, 2327 medium voltage, and 921.100 low voltage. And finally, 920.721 consumers, including industries and other electrical consumers. A 20kV distribution voltage has been estimated, as there are several medium-voltage references in the zone, and only one has been defined for this estimation. The complexity of having different voltages doesn't improve the analysis.



Exposure and vulnerability assessment of ELECTRICITY

In the flood scenario considered for the case of Barcelona Metropolitan Area, the exposed electrical assets are the generation systems, substations, and distribution centers. In the specific case of AMB, given that its electrical generation is small compared to the consumption, it has been assumed that the electricity supply comes from outside AMB, and with this assumption, the exposed assets are the substations and distribution centers.

Assessing the probability of failure starts with the flood calculation for the electrical-exposed assets creating an influence area for each asset based on the installation's nominal voltage. Then intersection between the influence area and the flooded depth provide two values: the maximum depth within the influence area and the percentage of the flooded area. Probability of failure of the installation is assessed using the previously calculated values. The fragility curve shown in the figure on the right is used for the maximum depth and the result is multiplied by the percentage of the flooded area.



Impact assessment results

Once the risk is calculated, the data is classified on four different levels to display the effects on this hazard: low failure probability, medium failure probability, high failure probability and non-acceptable failure probability.

Reviewing the previous table, as expected, increasing the return period increases the failure probability of the electrical assets, and this effect is equally pronounced for a long-term projected period. To extract more results from the methodology, the repair time can be calculated using the empirical formula detailed in the paper. This information is displayed in the following table and indicates that the maximum time to repair all installations is up to 15 days, but this calculation assumes there are enough personnel to repair all installations simultaneously and enough electrical elements to replace. For this reason, if several installations are affected, the time may increase. These values depend on factors not available for the project.

Once the risk is calculated, the data is classified on four different levels to display the effects on this hazard: low failure probability, medium failure probability, high failure probability and non-acceptable failure probability.

Return period	Maximum Repair Time (days)			
	Climate change projection period			
	Historic	2015-2040	2041-2070	2071-2100
T1	0.34	2.46	2.47	1.28
T10	5.42	5.84	5.35	6.37
T50	9.18	10.53	10.65	11.45
T100	11.36	12.22	12.3	12.9
T500	14.63	15.18	15.29	13.60

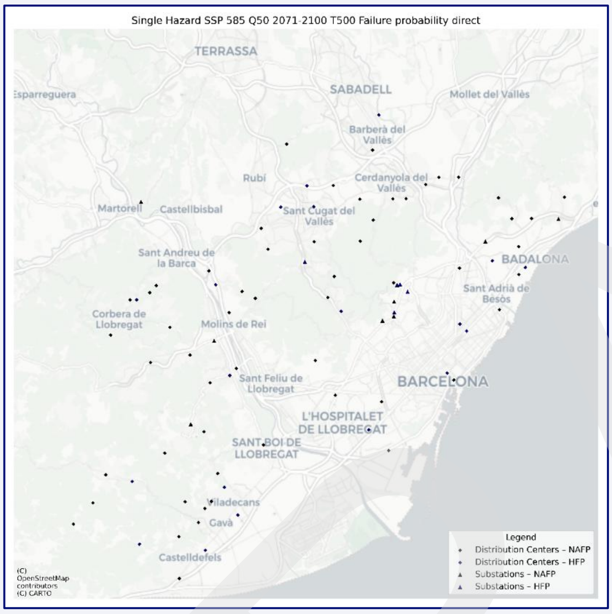
To obtain concrete economic results from the hazard risk assessment, the direct damage cost of electrical installations and the repair time are quantified in financial terms. The damage is calculated using the formulas detailed in Deliverable 3.1 (Guerrero-Hidalga et al., 2024). In summing up these last calculations, the damage cost is calculated using an empirical formula based on the installation voltage, the direct damage calculated, and the probability of failure. It also calculates the repair time using an empirical formula based on the damage (D).

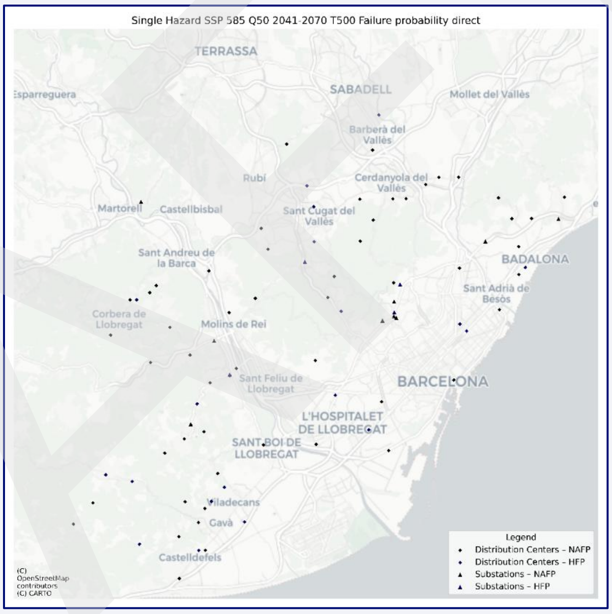
Return period	Damage Cost (M€)			
	Climate change projection period			
	Historic	2015-2040	2041-2070	2071-2100
T1	0.00	0.09	0.10	0.08
T10	2.70	2.85	2.36	3.02
T50	4.51	5.34	5.50	6.05
T100	6.31	6.69	6.85	7.51
T500	9.80	10.06	10.48	10.01

In conclusion, the data presented above reveal several points:

- The first point is the increase in cost for the baseline for frequent events (T1). The damage cost for electrical infrastructure at annual events ranges from 0.5 k€ (historic) to 92.3 k€ over the 2015-2040 period. This represents an increase of 180 times the historical value. Then the electrical infrastructure will suffer greater damage from events that were historically considered negligible. In these specific cases of T1, across all periods, it doesn't completely affect any installation, as shown in the first table.
- Analyzing the low probability and high impact scenarios (T500), the increase percentage compared to T1 is lower, but in absolute terms is high. The value cost is around 10 M€, with a maximum of 2041-2070 at 10.48 M€, and in the next period, it decreases a bit; this cost stabilization may suggest that the exposed assets are not increasing.

- From an engineering point of view, the historical benchmarks are not a valid baseline for infrastructure planning, as the intermediate term (2015-2040) far exceeds the historical records.
- In general, the electrical system needs an adaptation to the future as the increase across all return periods indicates that the system will not only suffer more severe floods but that assets previously located in "safe zones" will now be more exposed to flood risk.
- To end these conclusions, there is an anomaly in the data detected in the last century compared with the others, where the Repair Time (RT) and the Damage Cost (DC) decrease. This result is because the affected zones have fewer critical installations than in previous cases; the maximum water depth is high, but the zones differ. The following two images show the directly affected installation and distribution centers. Where shows the different affected installations and the change of zone affectations.

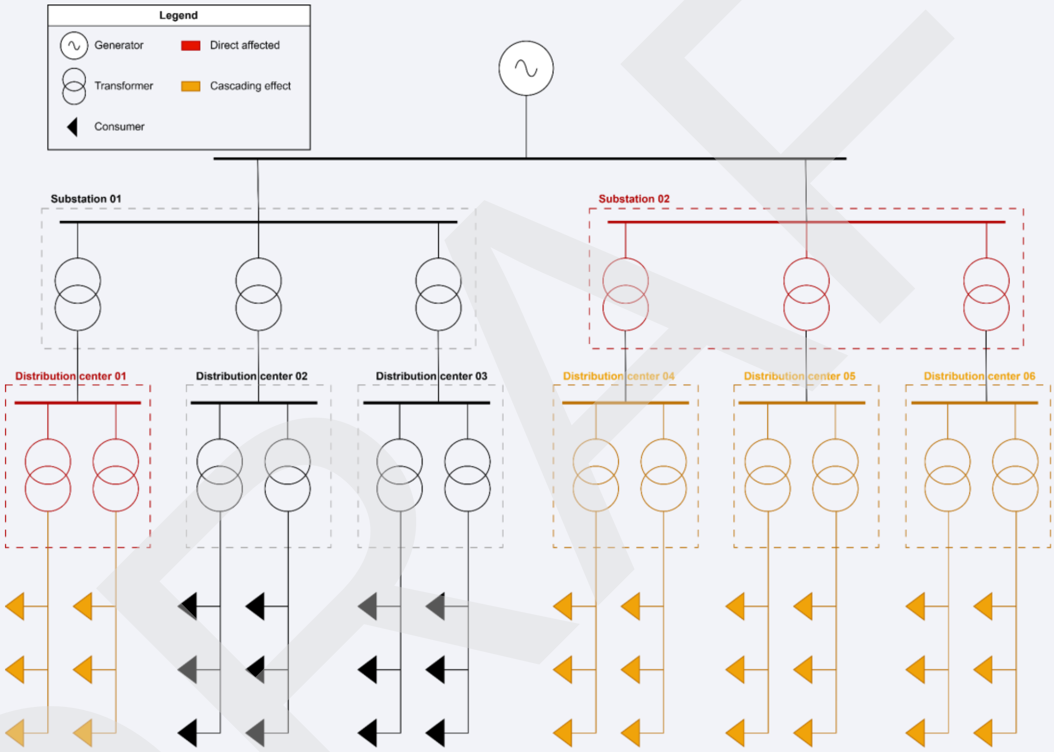




5.1.10 Cascading effects related to the single hazard

Indirect economic damage and cascading effects of FLOODS on ELECTRICITY
Cascading risk assessment methodology
The analysis of the cascade effect on the electrical system is a complex calculation involving many interactions between electrical assets, and it is often difficult to obtain all the information needed to perform it. This analysis examines the cascade effect on the electrical system under two key assumptions: first, that energy generation is centralized and not influenced by supply availability at substations, thereby treating energy supply as infinite. Second, it assumes the grid operates in a radial configuration, meaning that once a distribution center or substation is compromised, all consumers served by that station are affected, with no alternative pathways.

With this premise, to calculate the cascading effect, all electrical assets directly affected by a flood will cause a supply interruption to their consumers. Under the previous assumptions, the electrical system flows from generation to the high-voltage lines, then to the substations, to the distribution centers, and finally to the consumer. If any electrical asset on this chain fails, all elements below it fail as well. At the end, the problem is reduced to a topological search from the affected assets, already calculated in this document, to the lowest level: the consumers. This approach ensures a comprehensive understanding of potential failure paths, instilling confidence in the analysis.
Once all affected consumers have been identified, the effects on the electrical system can be quantified as explained in on the methodology proposed by Sánchez-Muñoz et al., 2020., and the operational costs associated with these effects can be calculated. First, calculating the energy not supplied, which is an economic cost for the electrical company (ENSC). The second significant value is the additional cost of maintaining supply to affected consumers, which is calculated based on the cost of providing energy via an auxiliary generator (AGC).



With this premise, to calculate the cascading effect, all electrical assets directly affected by a flood will cause a supply interruption to their consumers. Under the previous assumptions, the electrical system flows from generation to the high-voltage lines, then to the substations, to the distribution centers, and finally to the consumer. If any electrical asset on this chain fails, all elements below it fail as well. At the end, the problem is converted into a topological search from the affected assets to the lowest level, the consumers. This approach ensures a comprehensive understanding of potential failure paths, instilling confidence in the analysis.
Once all affected consumers have been identified, the effects on the electrical system can be quantified as explained in Sánchez-Muñoz et al., (2020), and the operational costs associated with these effects can be calculated. Firstly, calculating the energy not supplied, which is an economic cost for the electrical company (ENS) and, secondly, a significant value is the additional cost of maintaining supply to affected consumers (this value is calculated based on the cost of providing energy via a gasoil generator).

Cascading effect results

Using the results of the risk assessment on the electricity of the AMB, the following table shows information about the consumers and electrical assets affected by the cascading effects.

Return period	Affected consumers			
	Climate change projection period			
	Historic	2015-2040	2041-2070	2071-2100
T1	0	0	0	0
T10	1173	1173	977	1480
T50	5879	6488	6856	7248
T100	7341	7428	7428	7610
T500	14774	14895	14898	11978

Return period	Affected installations only cascading			
	Climate change projection period			
	Historic	2015-2040	2041-2070	2071-2100
T1	0	0	0	0
T10	0	0	0	0
T50	1	1	1	0
T100	0	0	0	1
T500	18	18	17	1

Return period	Affected installations total			
	Climate change projection period			
	Historic	2015-2040	2041-2070	2071-2100
T1	0	0	0	0
T10	9	9	8	10
T50	19	21	22	25
T100	27	29	29	30
T500	43	44	45	46

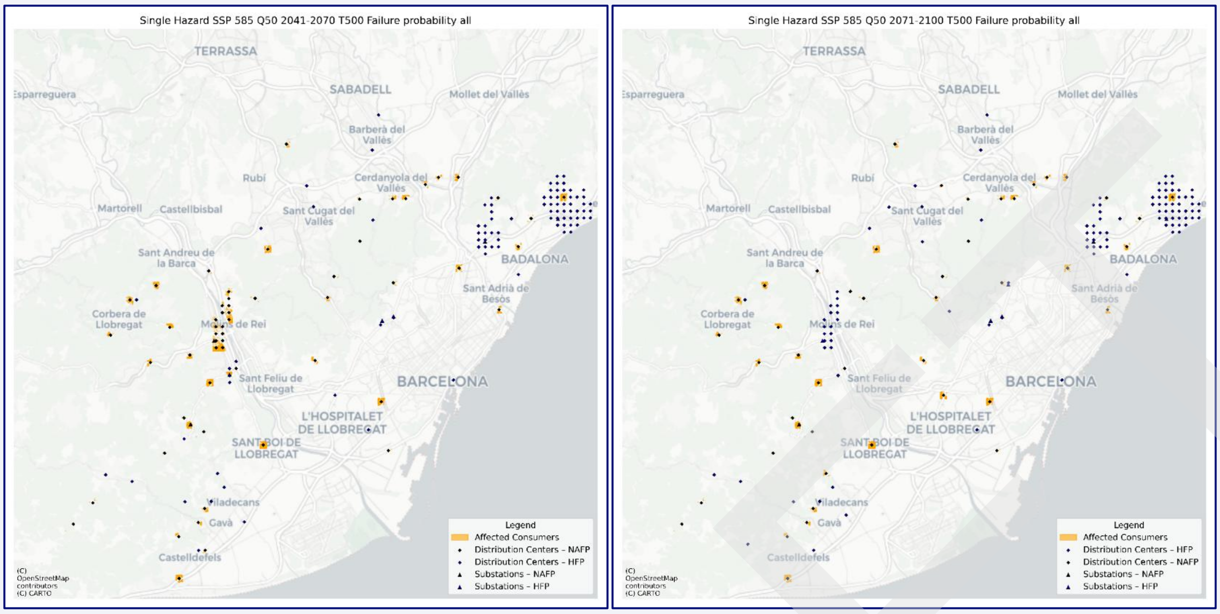
As shown in the table, similar to the direct effects on electricity, the cascading effects also increase the affected installations and consumers in high-impact events (T500). On T1, across all periods, it shows 0 cascading effects, since the issue affects only the directly affected installations, which have redundant systems. The number of consumers affected on T50 increases by 23%, from 5.879 (historic) to 7.248 in the last projected period. Even at T10, the affected consumers increased from 1.173 (historic) to 1.480 in the previous period.
The anomaly detected on the Direct impacts are also reflected in the cascading effects. In the table affected installations only cascading, do not increase as the direct impacts because in some cases when an installation is affected by a cascading effect, it means that the water is close and if in the next period arrives the water then this installation passes to the direct affected, also this effect is because of the non-regular distribution of the electrical installations.

Return period	Energy None Supplied Cost (k€)			
	Climate change projection period			
	Historic	2015-2040	2041-2070	2071-2100
T1	0.02	8.23	8.93	8.66
T10	104.65	108.90	98.44	112.65
T50	153.43	165.63	171.99	180.60
T100	191.47	181.82	183.99	196.10
T500	227.17	230.60	239.86	228.68

Return period	Auxiliar Generation Cost (M€)			
	Climate change projection period			
	Historic	2015-2040	2041-2070	2071-2100
T1	0.00	0.12	0.13	0.11
T10	2.14	2.22	1.99	2.36
T50	3.45	4.00	4.30	4.56
T100	4.62	4.80	4.88	5.20
T500	6.10	6.26	6.49	6.18

The last table shows the cost of the energy not supplied and the auxiliary generation cost required to maintain supply to consumers during repairs. From this table, it is possible to see a massive increase in the energy non-supplied cost between the projected periods on T1, from 0,0216 to 8.6 k€, but on the other hand, in the return periods, it is not much higher. In terms of auxiliary generation costs, they're much higher than the energy not supplied, and they increase over time.

In the last part of the century and T500 return period reflects the same issue observed on the direct impacts where the economic costs are a bit less, but the number of installations increases, the reason for this is that more small installations are affected but gives less impact to the electrical system. In the following images, the cascading effect on the two periods can be seen, where the affected installations are similar, but the risk slightly increases in one zone and decreases in the other, affecting fewer consumers depending on the zone.



In summary, the cascading effects of electricity directly affect electricity companies, increasing their costs. On the one hand, the energy not sold to consumers; on the other hand, the costs of maintaining the supply using alternative methods. This last is the costliest, as the way to supply the energy is not ideal.

5.2 Multi-hazard risk assessment

The essential difference between the single-hazard and multi-hazard scenarios of the AMB CS is the presence of the ESL boundary conditions in the sewer network outfalls discharging into the sea. Causing a backwater effect, seawater can reduce the discharge capacity of these points of the drainage infrastructure and, potentially, cause larger floods in low-lying coastal areas. The following sections show the multi-hazard events' impact on multiple risk receptors and compare these results with those obtained in the single-hazard scenario (Section 5.1).

5.2.1 Multi-hazard risk on people

Multi-hazard risk assessment of COMPOUND FLOODS on PEOPLE

Multi-hazard risk assessment methodology

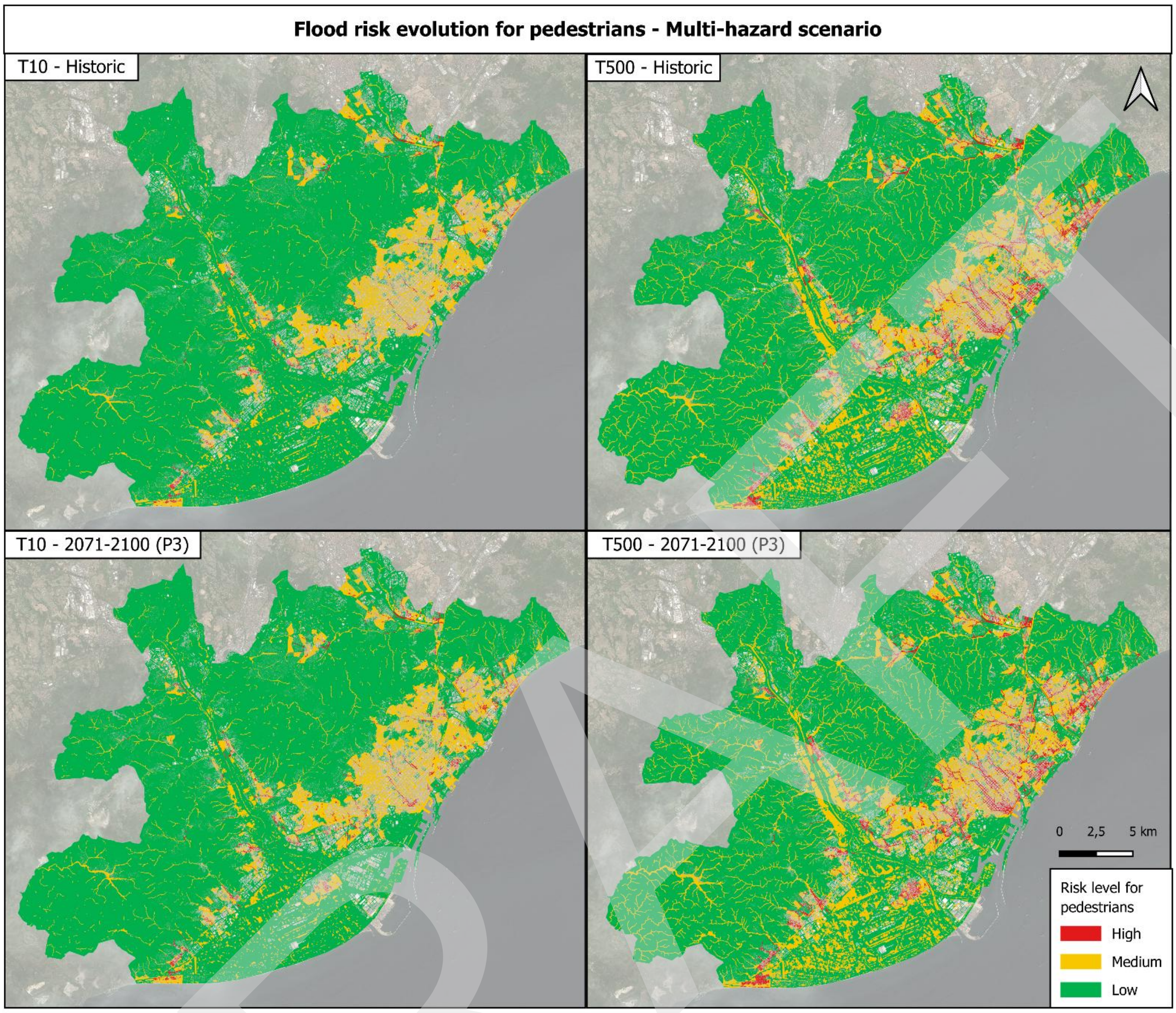
The methodology used for this multi-hazard risk assessment is the same as presented in Section 5.1.1. The difference between the scenarios concerns the hazard assessment dimension as explained in Sections 4.2.1 (AMB CS hazard assessment model) and 4.3.1 (AMB CS risk assessment scenarios).

Multi-hazard risk assessment results

The multi-hazard flood results in the following table shows the total area classified as high risk for pedestrians for all the simulations considering coincident extreme precipitation and storm surge conditions. Similar to the single hazard simulations, this data shows that the risk for pedestrians grows with the return period and climate change projection period. With respect to the historic scenario, growths of 6.6 to 12.9% are observed for the Period 1 simulations, 8.7 to 17.2% for Period 2, and 8.8 to 26.1% for Period 3. The largest increase is observed in the lower return period events. The reason for this is the higher climate change coefficients corresponding to these rainfall events in comparison to higher intensity and lower frequency cases.

	Area of HIGH flood risk on pedestrians for the return periods considered (ha) (and percentage of increase with respect to historic event)				
Projection Period	**T1**	**T10**	**T50**	**T100**	**T500**
Historic	1.69	513.02	952.08	1208.21	1798.78
2015-2040	22.73	579.34 (+12.9%)	1042.69 (+9.5%)	11299.32 (+7.5%)	1916.64 (+6.6 %)
2041-2070	23.99	601.15 (+17.2%)	1085.16 (+14.0%)	1333.94 (+10.4%)	1955.57 (+8.7%)
2071-2100	34.20	647.06 (+26.1%)	1185.93 (+24.6%)	11463.34 (+21.2%)	1956.82 (+8.8%)

The spatial distribution of medium and high-risk areas is very similar to the single-hazard simulations. Risk areas representation for T10 (Historic and Period 3) and T500 (Historic and Period 3) shows that medium and high-risk concentrate in the preferential water paths. In particular, high-risk areas are located in the intersection between flood-prone urban areas and highly populated areas, typically in the urban centers of the municipalities in the AMB. Important floodable areas in peri-urban environments remain at medium risk due to the lower exposure and vulnerability metrics.

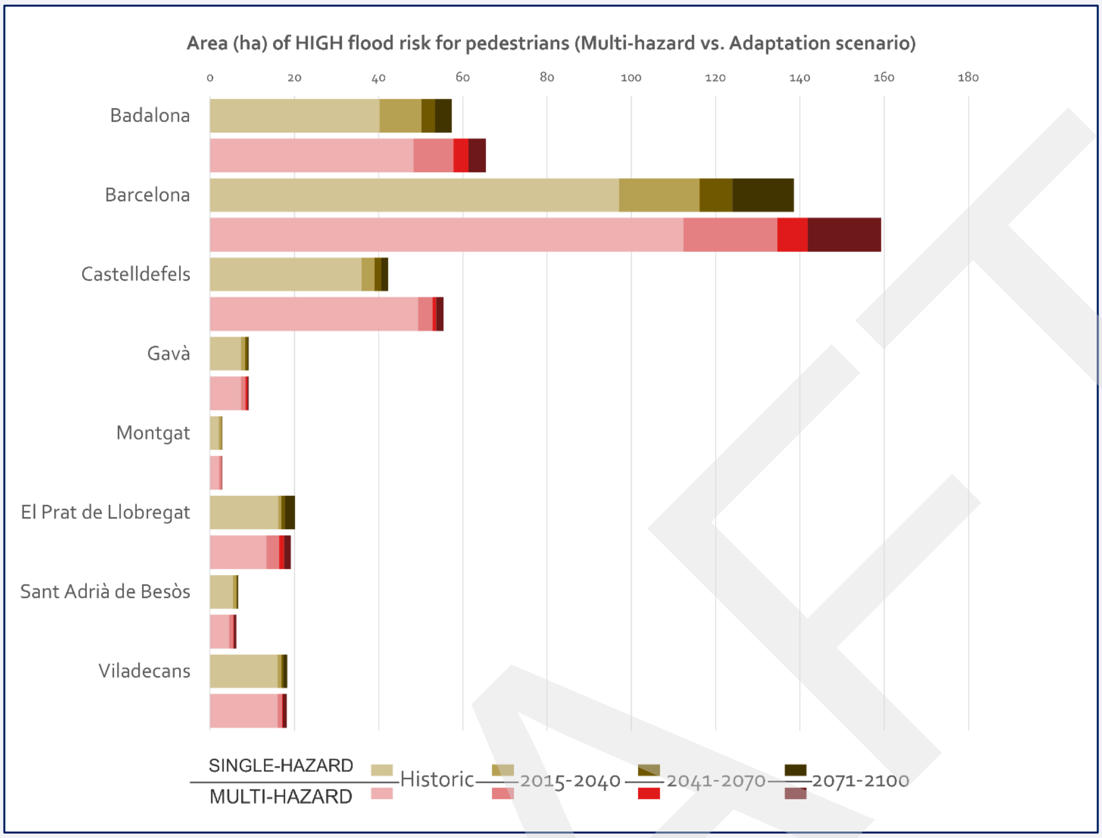


Comparison between the single-hazard and multi-hazard scenarios

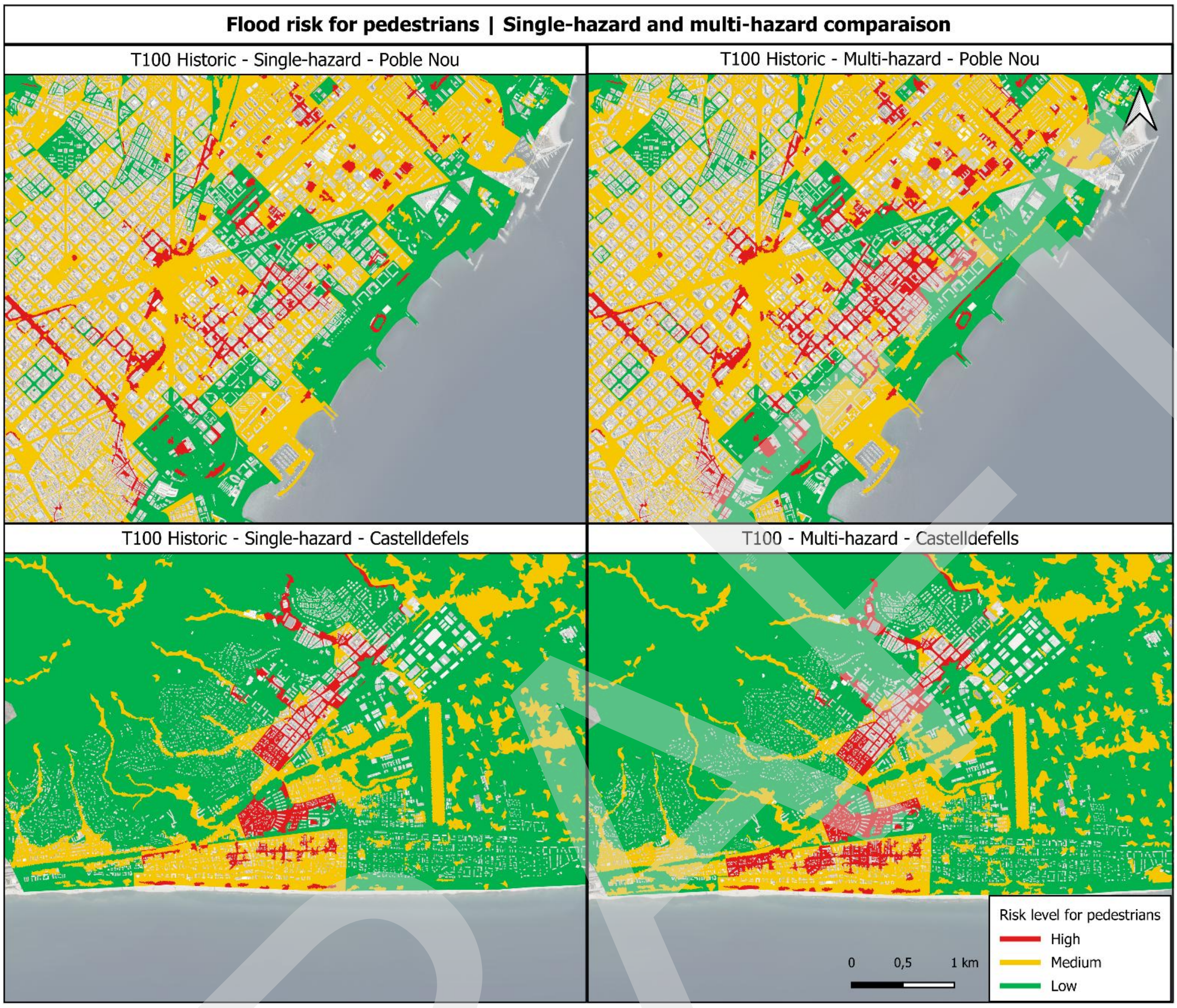
The combined effect of extreme precipitation and storm surge can significantly affect the risk condition for pedestrians in the AMB. As shown in the table below, the high-risk area grows for all return periods and climate change projections considered. For frequent rain events (T1), growths are very significant. T10, T50, and T100 show sustained growth between 4 and 8%. However, from some T500 events, this growth seems to be minimal. The reasons for this are as follows: firstly, the extreme rainfall intensity associated with a T500 event prevails over the effect of the sea level, thus, the results are statistically more similar; secondly, computational limitations of such events can limit the accuracy in some areas for the multi-hazard simulations.

Return period	Modelling scenario	High-risk area for pedestrians (ha)			
		Climate change projection period			
		Historic	2015-2040	2041-2017	2071-2100
T1	Single-hazard scenario	0.00	19.42	20.94	31.54
	Multi-hazard scenario	1.69	22.73	23.99	34.20
	Difference	100%	17%	15%	8%
T10	Single-hazard scenario	494.14	554.06	577.69	620.75
	Multi-hazard scenario	513.02	579.34	601.15	647.06
	Difference	4%	5%	4%	4%
T50	Single-hazard scenario	918.68	987.67	1007.35	1121.02
	Multi-hazard scenario	952.08	1042.69	1085.16	1185.93
	Difference	4%	6%	8%	6%
T100	Single-hazard scenario	1174.76	1245.11	1270.60	1400.63
	Multi-hazard scenario	1208.21	1299.32	1333.94	1463.34
	Difference	3%	4%	5%	4%
T500	Single-hazard scenario	1818.69	1856.01	1879.70	1972.91
	Multi-hazard scenario	1798.78	1916.64	1955.57	1956.82
	Difference	0%	3%	4%	0%

Given that the multi-hazard scenario considered involves the interaction between runoff evacuation through sewer systems and the sea level, it is logical that the increase in risk is located in the low-lying and flood-prone coastal areas. The following graphs reflect that the high-risk areas grow significantly in the 8 coastal municipalities of the AMB. Barcelona, Badalona, and Castelldefels show the highest growth. These cases have largely affected areas by the seaside, where the sea's interaction with the sewers can facilitate extensive intrusion of seawater inland and drastically reduce the local drainage capacity. On the contrary, el Prat del Llobregat urban center is located inland despite being a coastal municipality. Consequently, the risk increase is much lower.



The geographic representation of risk classification in two example coastal areas: the Poblenou neighborhood in Barcelona and Castelldefels Platja. In both cases, it can be observed that the multi-hazard scenarios largely increase medium and high-risk areas in the flood-prone areas already identified in the single-hazard scenario. This illustration represents the fact that, even if the growth of high-risk areas in multi-hazard scenarios might seem low at the metropolitan scale, it can largely increase risk conditions in certain coastal areas. There, the percentage increase of high-risk surfaces would be very significant.



5.2.2 Multi-hazard risk on transport

Multi-hazard risk assessment of COMPOUND FLOODS on TRANSPORT

Multi-hazard risk assessment methodology

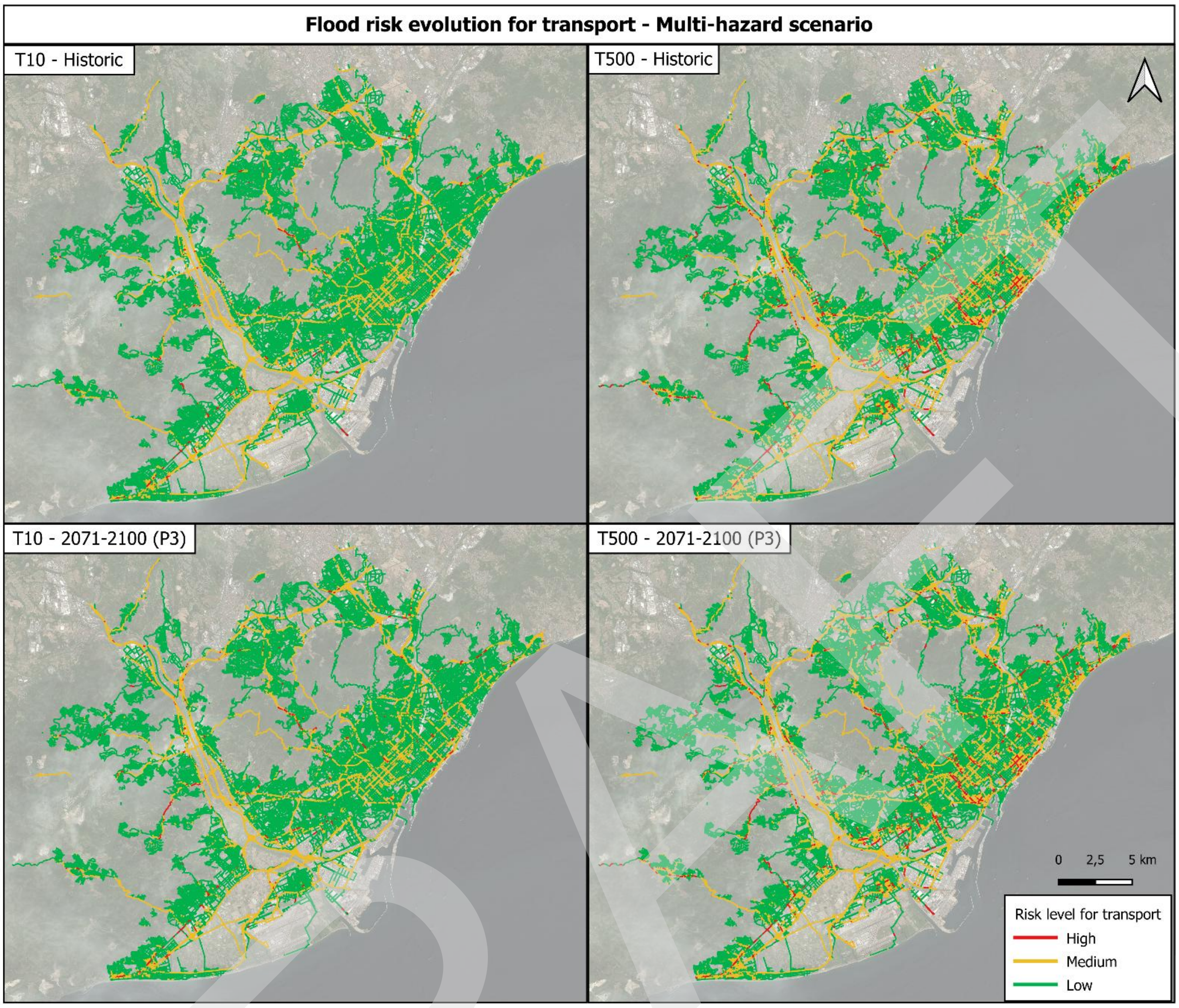
The methodology used for this multi-hazard risk assessment is the same as presented in Section 5.1.2. The difference between the scenarios concerns the hazard assessment dimension as explained in Sections 4.2.1 (AMB CS hazard assessment model) and 4.3.1 (AMB CS risk assessment scenarios).

Multi-hazard risk assessment results

The multi-hazard flood results in the following table, which shows the total kilometers of transportation network classified as high risk for vehicle circulation for all the simulations in the multi-hazard scenario. The risk response to growing return periods and future climate projection periods is similar to the single-hazard simulations. Comparing future scenarios to historic events, growths of 7.3 to 13% are observed for the Period 1 simulations, 9.8 to 19.3% for Period 2, and 12.2 to 28.4% for Period 3. Lower return periods show higher increases in comparison to less frequent events. As observed in the risk for pedestrians, the higher climate change coefficients applied to T1 events lead to more drastic percentual increases in high-risk indicators.

	Area of HIGH flood risk on transport for the return periods considered (km) (and percentage of increase with respect to historic event)				
Projection Period	**T1**	**T10**	**T50**	**T100**	**T500**
Historic	0.08	59.05	124.28	163.88	274.77
2015-2040	3.84	66.70 (+13.0%)	137.41 (+10.6%)	177.45 (+8.3%)	294.77 (+7.3%)
2041-2070	3.91	70.42 (+19.3%)	142.53 (+14.7%)	183.57 (+12.0%)	301.79 (+9.8%)
2071-2100	4.95	75.79 (+28.4%)	159.00 (+27.9%)	207.18 (+26.4%)	308.30 (+12.2%)

The following maps illustrate the spatial distribution of low, medium, and high-risk areas in the transportation network for multi-hazard T10 and T100 events in the historic and long-term (P3) periods. Most medium and high-risk links correspond to the highways, roads, and main streets in flood-prone areas. In particular, a large number of them are located in the lower coastal areas where the multi-hazard conditions generate severe flood conditions. Most residential streets remain in low-risk conditions.

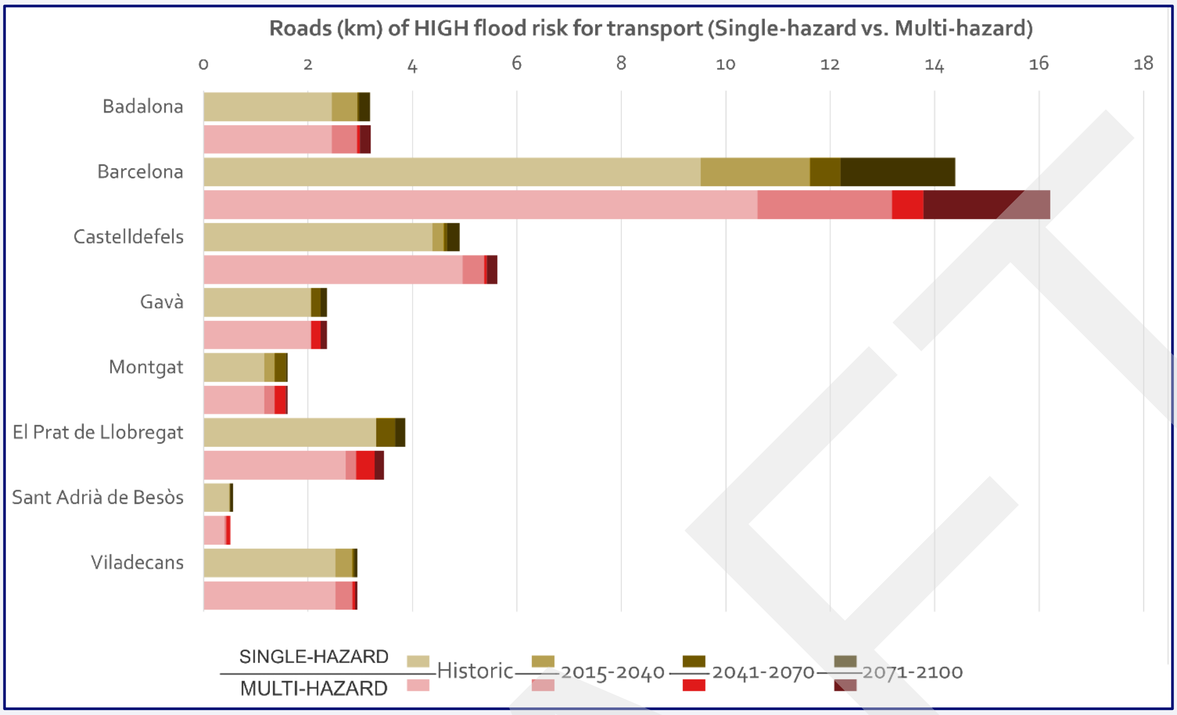


Comparison between the single-hazard and multi-hazard scenarios

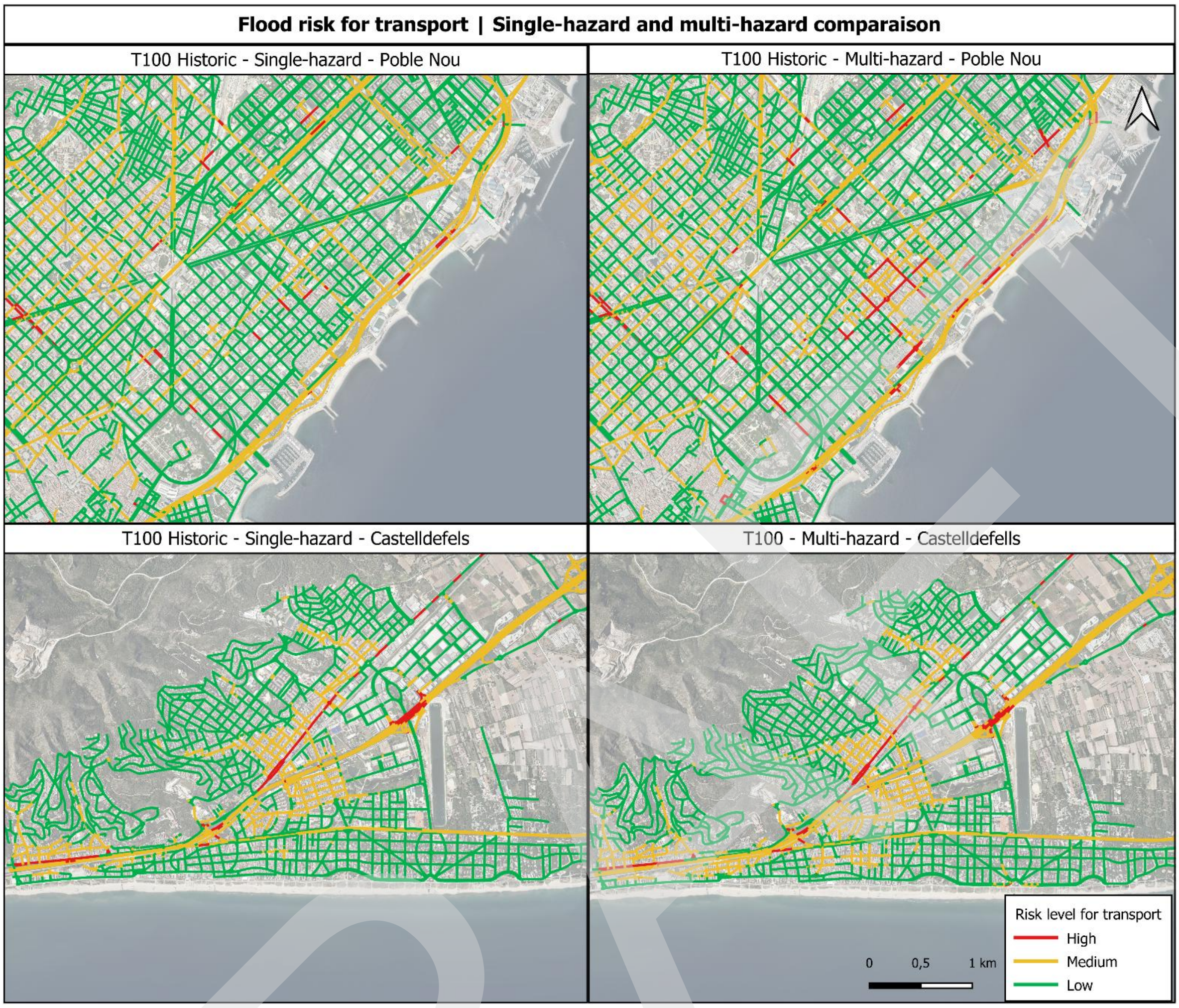
The following table compares the total extent of the high-risk transportation network between the single-hazard and multi-hazard scenarios. It can be observed that growth rates, between 0 and 5%, are fairly homogeneous among all return periods and projection periods. No particular trend can be observed between the most and least frequent events considered. Nevertheless, it can be concluded that the multi-hazard conditions tend to worsen the risk situation on the road network in case of combined foods.

Return period	Modelling scenario	High-risk roads for transport (Km)			
		Climate change projection period			
		Historic	2015-2040	2041-2017	2071-2100
T1	Single-hazard scenario	0.09	3.64	3.66	5.01
	Multi-hazard scenario	0.08	3.84	3.91	4.95
	Difference	0%	5%	7%	0%
T10	Single-hazard scenario	59.11	65.32	69.37	74.37
	Multi-hazard scenario	59.05	66.70	70.42	75.79
	Difference	0%	2%	2%	2%
T50	Single-hazard scenario	120.54	132.45	135.54	151.54
	Multi-hazard scenario	124.28	137.41	142.53	159.00
	Difference	3%	4%	5%	5%
T100	Single-hazard scenario	160.17	172.55	175.47	198.88
	Multi-hazard scenario	163.88	177.45	183.57	207.18
	Difference	2%	3%	5%	4%
T500	Single-hazard scenario	271.26	282.11	287.24	306.55
	Multi-hazard scenario	274.77	294.77	301.79	308.30
	Difference	1%	4%	5%	1%

When results are discretized in the 8 coastal municipalities, it can be observed that the local growth rates of high-risk areas are more significant than in the global metropolitan data. The data in the graph below corresponds to the total high-risk length of transportation links for single and multi-hazard T10 events (historic, P1, P2, and P3). In Barcelona, the growth range is between 11% and 12% among the four climate scenarios. In Castelldefels the change is 13% for the historic period to 5% for the third period considered. The growth rates in the other municipalities remain similar for both scenarios.



Given that this scenario considers a storm surge – rainfall interaction, inland sections of the transportation network are logically unaffected. In order to exemplify the risk growth at the local scale The following figure compares the Poblenou neighborhood in Barcelona and Castelldefels Platja for the historic T100 event under single and multi-hazard conditions. Similarly, as for the pedestrian risk assessment, the multi-hazard scenarios significantly increase medium and high-risk areas in the flood-prone areas already identified in the single-hazard scenario. Again, the apparently low changes in risk at the metropolitan scale involve significant increases of high-risk surface in particular coastal areas.



5.2.3 Multi-hazard risk on properties

Multi-hazard risk assessment of COMPOUND FLOODS on PROPERTIES

Multi-hazard risk assessment methodology

The methodology used for this multi-hazard risk assessment is the same as presented in Section 5.1.3. The difference between the scenarios concerns the hazard assessment dimension as explained in Sections 4.2.1 (AMB CS hazard assessment model) and 4.3.1 (AMB CS risk assessment scenarios).

Multi-hazard risk assessment results

For the multi-hazard risk assessment considered the same time horizons (Historic, 2015-2040, 2041-2070 and 2071-2100) and return periods (T1, T5, T10, T50, T100 and T500) as the single-hazard scenario.

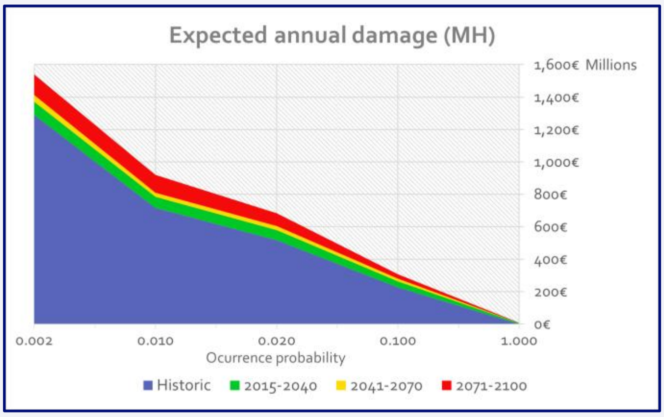
The results presented in the following table, show that the combined hazard of pluvial floods and storm surges present a considerable risk increment for a coastal area such as the AMB. Historic data shows that in the current status, this combined event could mean suffering damages of 226M € for a T10 and 1.290M € for a T500 event. As climate conditions and stability worsen in future climate projections studied, these damages could increase 35.6% for the T10 event and 19.2% for the T500 event.

As mentioned in the single-hazard risk section, T1 events present a dramatic rise in economic impact when comparing the historic data with future projections. This is caused by the climate change factors applied to this event, which correspond to a T2 or T3 event according to the historic IDF curves of Barcelona.

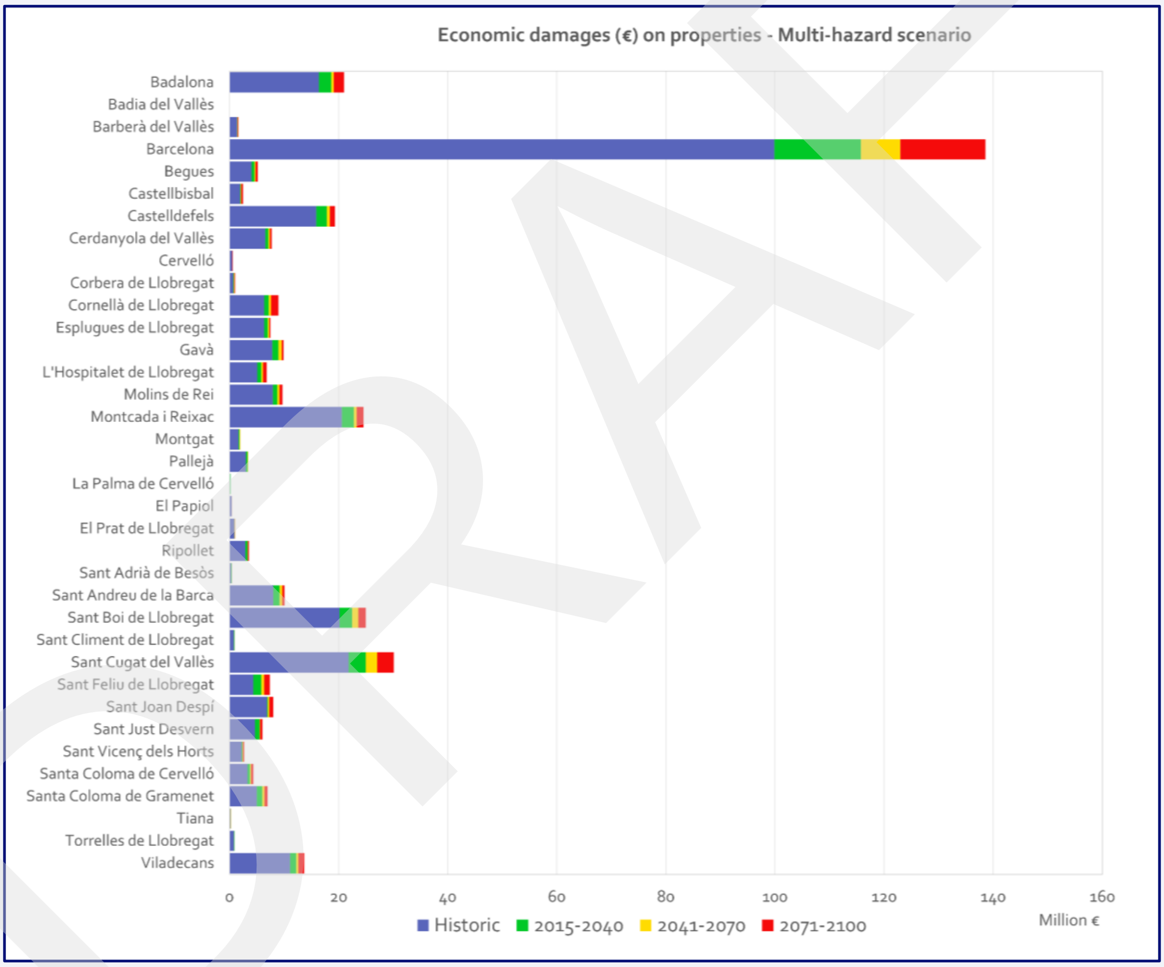
	Economic damage on properties for the return periods considered (and percentage of increase with respect to historic event)					
Projection Period	**T1**	**T10**	**T50**	**T100**	**T500**	**Expected annual damage**
Historic	146,230 €	226,365,990 €	516,912,623 €	717,067,794 €	1,290,545,724€	145,862,000 €
2015-2040	4,784,343 €	264,046,932€ (+16.6%)	579,766,314 € (+12.2%)	785,758,085 € (+9.6%)	1,371,539,915 € (+6.3%)	170,183,418 € (+16.7%)
2041-2070	5,199,993 €	279,589,968 € (+23.5%)	603,306,386 € (+16.7%)	809,458,901 € (+12.9%)	1,412,851,601 € (+9.5%)	179,424,405 € (+23.0%)
2070-2100	8,122,733 €	306,932,753 € (+35.6%)	683,404,915 € (+32.3%)	919,833,749 € (+28.3%)	1,538,779,186 € (+19.2%)	199,239,120 € (+36.6%)

Results show the evolution of economic impact on properties for the AMB through the different scenarios, as well as the increase in Expected Annual Damage. This metric offers a general view that summarizes events with different probability of occurrence. It shows a steady increase in EAD through the time periods analyzed coming up to a 36.6% increase in damages for the furthest future projection meaning an expected annual damage of 199M € per year on buildings of the AMB.

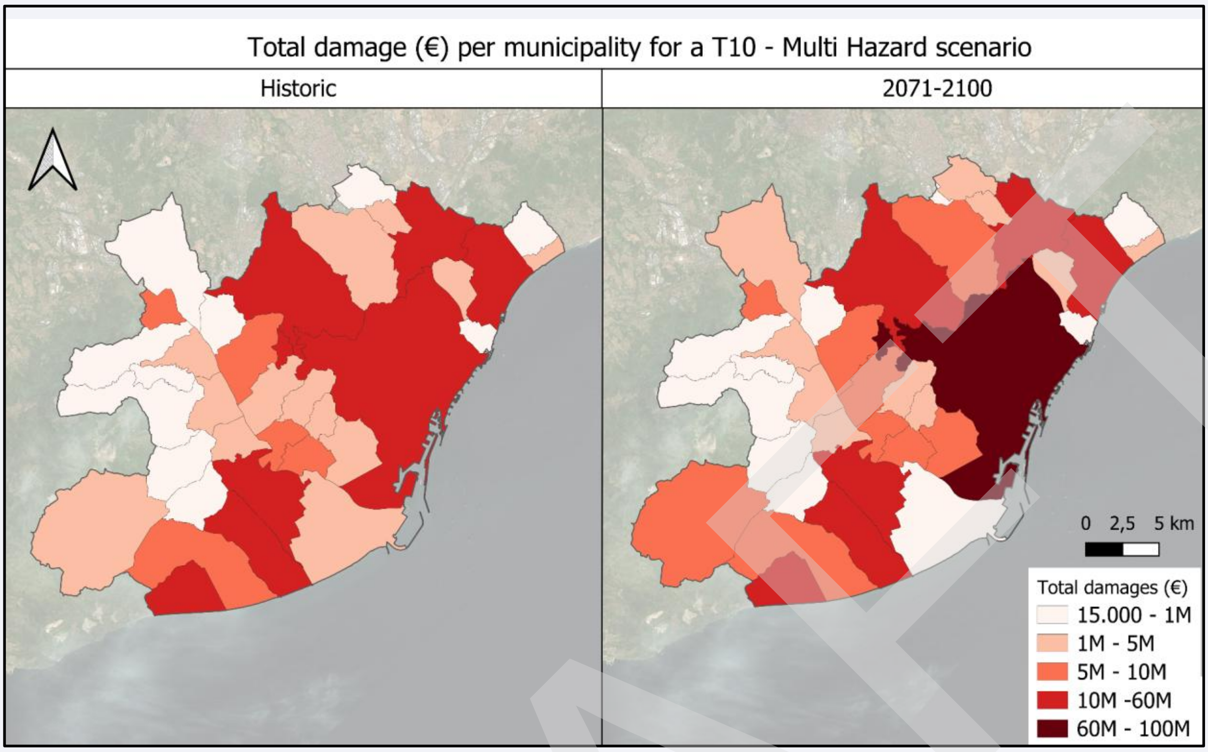
A more detailed view into the impact of this multi-hazard scenario on each municipality shows that Barcelona is still clearly the most affected municipality in total damages. The graph below reflects the estimated monetary loss of each municipality for the different time horizons and a T10 event. Barcelona reaches up to 138M € of economic impact for the period between 2071 and 2100 in the scenario described by the SSP 585. Most of the other municipalities don't reach 20M € except for Sant Cugat del Vallès, Sant Boi de Llobregat, Montcada i Reixac and Badalona.



The graph below shows another interesting perspective, the economic impact taking into account also the population of each municipality. When analyzed this way, some municipalities such as Begues (768€/capita), Montcada i Reixac (705€/capita) or Santa Coloma de Cervelló (542€/capita) are brought to attention. The size of these municipalities shows a total damage that seems small, but when compared this way it becomes clear how much an event of these characteristics could affect their population.



The figure below presents the economic damage of a T10 compound event for each municipality on a map of the AMB. It shows how Barcelona is the most affected area, surpassing the 100 M € in damages for the projection period of 2071-2100.



Comparison between the single-hazard and the multi-hazard scenarios

As it can be observed, the effects produced by coincident occurrence of a precipitation event and a storm surge are significant for all return periods and projection periods considered. Thus, the backwater effect is a significant phenomenon for the AMB, which can severely increase the economic damage of an event. When comparing the S.H. and M.H. simulations, the relative increase of damage is observed to decrease with the event frequency. In other words, the higher the return period, the lower the difference between the scenarios results. This can be attributed to the fact that for T1 events, the main driver of the economic damages is the ESL condition, while for the rest of the events, precipitation causes most of the economic damage.

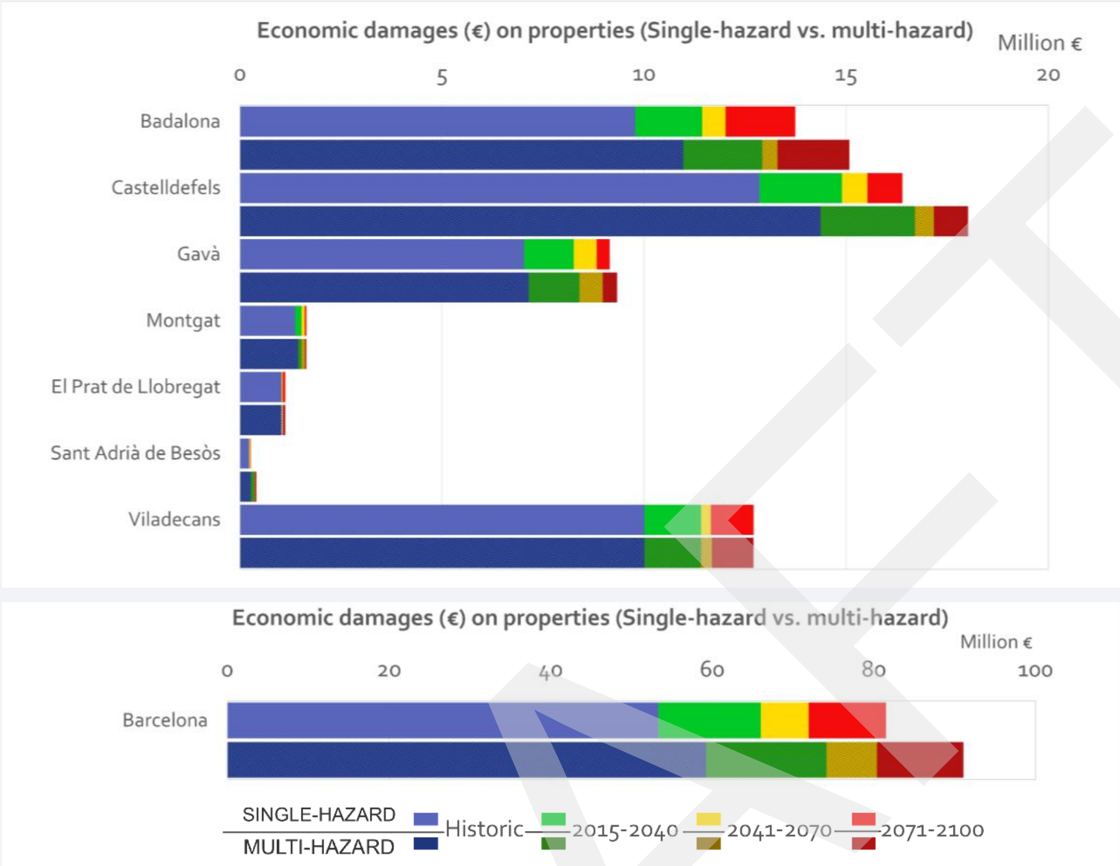
For T10 events, the multi-hazard conditions the total damage can increase 4 or 5% with respect to single-hazard conditions, depending on the effect of climate change. For T50, T100, and T500, these increases range between 5 to 7%, 5 to 6%, and 4 to 15%, respectively.

In terms of climate change, except for T1, no significant differences are observed in the percentage of damage increase among the different climate change projection periods for the same return period. In fact, the damage increase between the S.H. and M.H. scenarios seem to be slightly higher in the historic events than in the long-term projection. This can be explained as follows: the larger the rainfall intensity, the less significant the effect of the sea level boundary condition. Since the long-term projections provide more severe design storms than the historic ones, results for the period between 2071 and 2100 are less affected by the ESL condition, so the differences between S.H. and M.H. results are smaller.

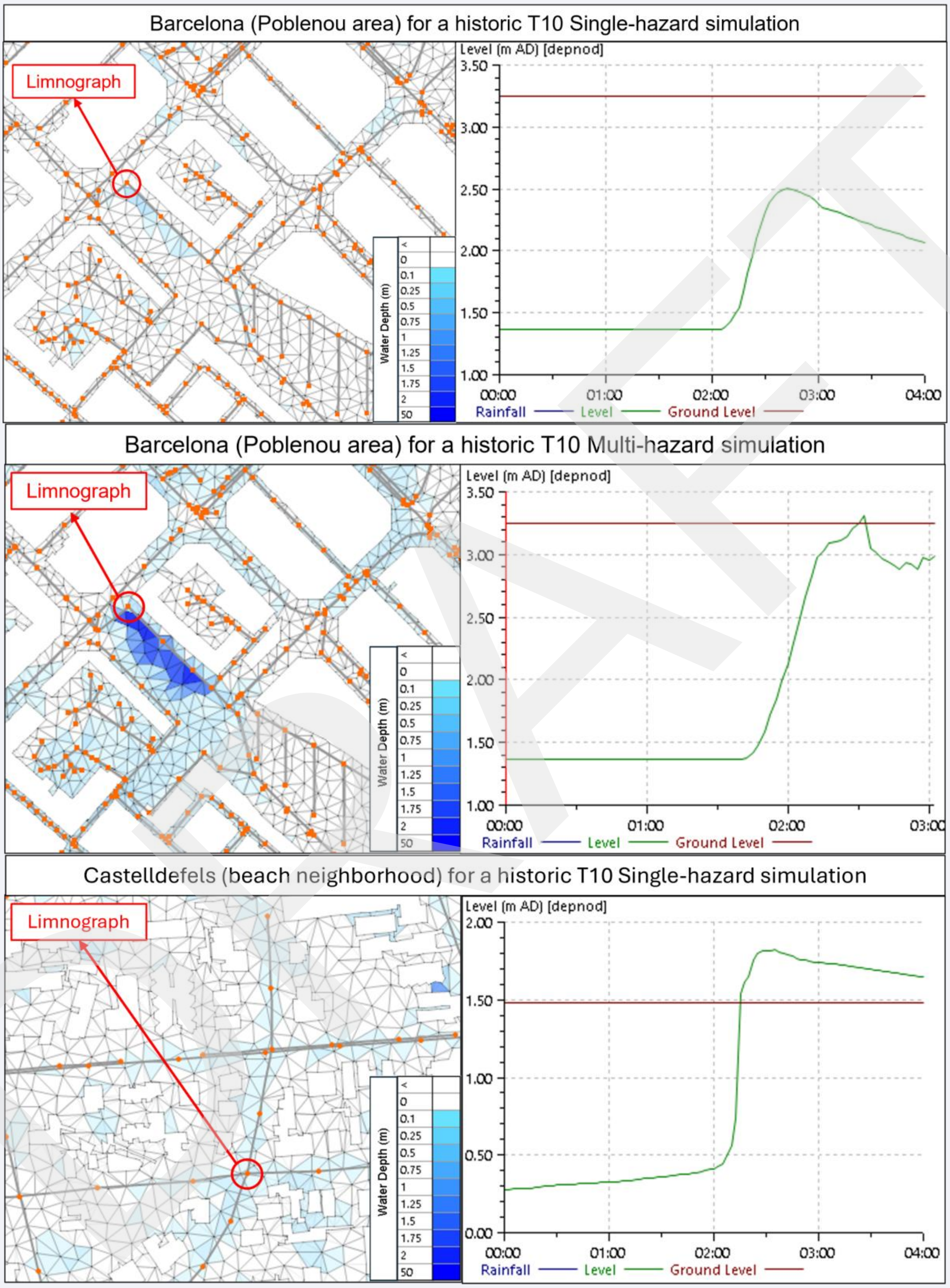
According to the above, the expected annual damage for the M.H. scenarios is larger than that of the S.H. by a 5% approximately. It should be also noted that, according to the simplified approach applied in this case, results could be quite conservative. Anyway, the results show that the hazard and impact models are really sensitive to possible effects of backflow in sewers systems due to the coincidence of storm surges and heavy rainfall events.

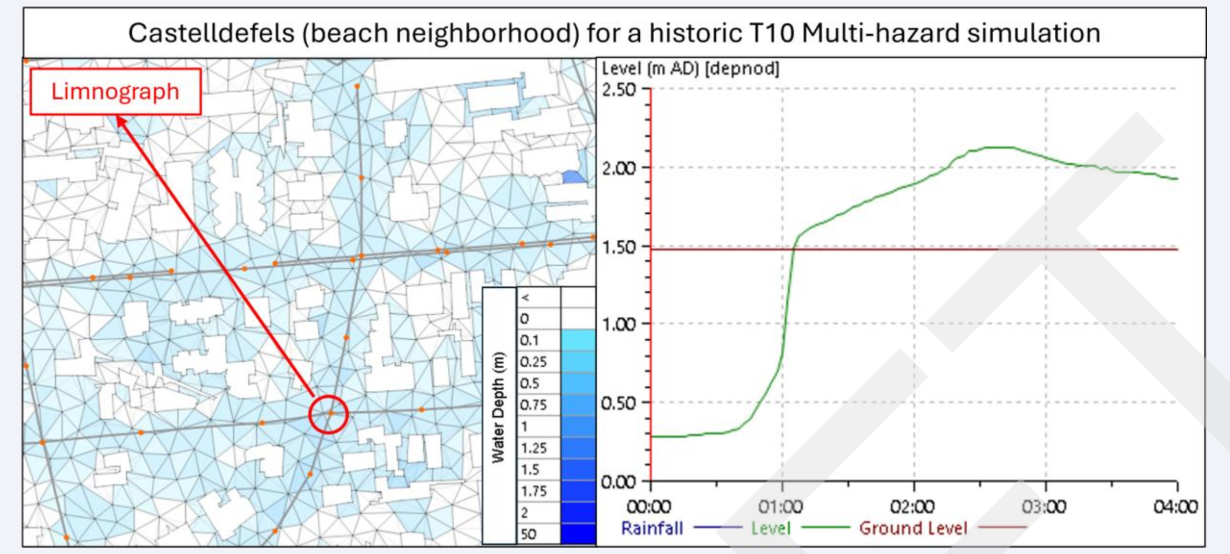
Return period	Modelling scenario	Climate change projection period			
		Historic	2015-2040	2041-2017	2071-2100
T1	Single-hazard scenario	0.01 M€	4.4 M€	4.8 M€	7.8 M€
	Multi-hazard scenario	0.15 M€	4.8 M€	5.2M€	8.1 M€
	Difference	1161%	9%	8%	4%
T10	Single-hazard scenario	217.4 M€	252.2 M€	267.8 M€	293.8 M€
	Multi-hazard scenario	226.4 M€	264 M€	279.6 M€	306.9 M€
	Difference	4%	5%	4%	4%
T50	Single-hazard scenario	493 M€	551.3 M€	565.4 M€	648.7 M€
	Multi-hazard scenario	516.9 M€	579.8 M€	603.3 M€	683.4 M€
	Difference	5%	5%	7%	5%
T100	Single-hazard scenario	685.1 M€	750.3 M€	767 M€	876.5 M€
	Multi-hazard scenario	717.1 M€	785.8 M€	809.5 M€	919.8 M€
	Difference	5%	5%	6%	5%
T500	Single-hazard scenario	1244.2 M€	1319.7 M€	1344.9 M€	1451.3 M€
	Multi-hazard scenario	1290.5 M€	1371.5 M€	1412.9 M€	1538.8 M€
	Difference	4%	15%	5%	6%
EAD	Single-hazard scenario	139.8 M€	163.3 M€	171,1 M€	190,4 M€
	Multi-hazard scenario	145.9 M€	170.2 M€	179.4 M€	199.2 M€
	Difference	4%	5%	5%	5%

Logically, since the multi-hazard model focuses on compound floods caused by the interaction of precipitation and ESL, the increase in damages is exclusively observed in the eight coastal municipalities of the AMB. The following figures compare the economic damages expected per municipality for the single-hazard (e.g., Badalona S.H.) and multi-hazard (e.g., Badalona M.H.). It can be observed that for all municipalities, the damages associated with the compound flood scenario are larger. This is particularly critical in Barcelona, Badalona, and Castelldefels. Cases like El Prat de Llobregat, Viladecans or Montgat, the sea level effect is not relevant.



From the figures and tables presented above, the following ideas can be extracted. At the metropolitan scale, the economic impact of multi-hazard events is only marginally higher than that of the single-hazard scenario. In fact, not all coastal municipalities within the AMB are sensitive to storm surge conditions in terms of flooding. This suggests that the increase in economic damage is concentrated in specific, localized areas of the AMB where multi-hazard conditions have a particularly strong influence, resulting in substantially more severe flooding and associated losses. To further illustrate this pattern, the figures below provide a closer view of the areas identified as hotspots for compound flood events. The first one shows the area of Poblenou in Barcelona, and the second one the coastal neighborhood of Castelldefels. All flood maps shown correspond to the simulation of a T10 historic design storm. In both cases, it can be observed that the floods are larger for the multi-hazard simulations, both in terms of extension and water depth. Furthermore, the limnograph (showing the water level evolution in the highlighted nodes) reflects that, as a result of the ESL boundary condition, surcharge conditions are reached in parts of the network that under a single-hazard scenario would remain in free flow conditions.


Barcelona (Poblenou area) for a historic T10 Single-hazard simulation
Limnograph
Water Depth (m)
Level (m AD) [depnod]
Rainfall
Level
Ground Level
Barcelona (Poblenou area) for a historic T10 Multi-hazard simulation
Limnograph
Water Depth (m)
Level (m AD) [depnod]
Rainfall
Level
Ground Level
Castelldefels (beach neighborhood) for a historic T10 Single-hazard simulation
Limnograph
Water Depth (m)
Level (m AD) [depnod]
Rainfall
Level
Ground Level



5.2.4 Multi-hazard risk for risk receptor Waste sector

Multi-hazard risk assessment of COMPOUND FLOODS on the WASTE SECTOR
Multi-hazard risk assessment methodology
The methodology used for this multi-hazard risk assessment is the same as presented in Section 5.1.4. The difference between the scenarios concerns the hazard assessment dimension as explained in Sections 4.2.1 (AMB CS hazard assessment model) and 4.3.1 (AMB CS risk assessment scenarios).
Impact assessment results
As the results below show, the same infrastructures from the waste sector are impacted by compound events than only pluvial floods. Still, infrastructures pertaining to the categories of local recycling centers, ecoparcs and compost plants would be impacted by the events simulated. Comparison between the single-hazard scenario and the multi-hazard show no difference in number or impact between the two. The reason behind this is the nature of the hazards considered and the geographical location of the waste assets. As already established, the hazards considered for this multi-hazard assessment are pluvial floods and storm surges. None of the 46 waste infrastructures analyzed are located within the scope of impact of storm surges as they are all in-land. This results on economic damages only pertaining the pluvial floods, which remain the same as in the single-hazard assessment.

Comparison between the single-hazard and the multi-hazard scenarios

Return period	Modelling scenario	Climate change projection period			
		Historic	2015-2040	2041-2017	2071-2100
T1	Single-hazard scenario	0	0	0	0
	Multi-hazard scenario	0	0	0	0
	Difference	-	-	-	-
T10	Single-hazard scenario	0.62 M€	0.96 M€	1.03 M€	1.05 M€
	Multi-hazard scenario	0.62 M€	0.96 M€	1.03 M€	1.05 M€
	Difference	-	-	-	-
T50	Single-hazard scenario	1.77 M€	1.83 M€	1.83 M€	1.91 M€
	Multi-hazard scenario	1.77 M€	1.83 M€	1.83 M€	1.91 M€
	Difference	-	-	-	-
T100	Single-hazard scenario	2.12 M€	2.24 M€	2.24 M€	2.64 M€
	Multi-hazard scenario	2.12 M€	2.24 M€	2.24 M€	2.64 M€
	Difference	-	-	-	-
T500	Single-hazard scenario	4.39 M€	5.15 M€	5.37 M€	5.96 M€
	Multi-hazard scenario	4.39 M€	5.15 M€	5.37 M€	5.96 M€
	Difference	-	-	-	-
EAD	Single-hazard scenario	0.43 M€	0.59 M€	0.63 M€	0.65 M€
	Multi-hazard scenario	0.43 M€	0.59 M€	0.63 M€	0.65 M€
	Difference	-	-	-	-

5.2.5 Multi hazard risk for risk receptor Electricity

Multi hazard risk assessment on ELECTRICITY

Risk assessment methodology

The risk assessment for this section follows the same methodology as outlined in section 5.1.9. In this instance, it utilizes the multi-hazard flood risk maps detailed in Section 5.2.

Electrical network topology of ELECTRICITY

The network topology is the same as that described in Section 5.1.9, enabling an easy comparison of the different risk assessments.

Exposure and vulnerability assessment of ELECTRICITY

The vulnerability assessment conducted follows the same principles outlined in section 5.1.9.

Impact assessment results

Similarly, as shown in section 5.1.9, several results will be presented and, on this occasion, compared with the single-hazard scenario.
The following table shows the repair time for each electrical installation and the comparison with. The important highlights regarding the reparation time are the following:

- Long-term Severity Escalation: Under the SSP5-8.5 high-emission scenario, repair times consistently increase over time. For a T500 return period, downtime increases from 14.53 days (Historic) to 15.8 days by the 2071–2100 horizon.
- The Multi-Hazard Penalty: The data highlights a significant "penalty" when compound hazards are considered. During the 2071–2100 period, the T1 event shows a 20.37% increase in repair time relative to single-hazard models, whereas the T500 event shows a 16.18% increase.
- Early Century Stabilization: In the 2015–2040 and 2041–2070 periods, intermediate return periods (T50, T100) show comparison ratios slightly below 100%. This suggests that for moderate events, the dominant hazard dictates the timeline, whereas extreme late-century scenarios trigger complex compound failures.

Return period	Maximum Repair Time (days) Single hazard difference (%)			
	Climate change projection period			
	Historic	2015-2040	2041-2070	2071-2100
T1	0.34 (0.21)	2.46 (0.00)	2.47 (0.00)	1.54 (20.37)
T10	5.35 (-1.3)	5.73 (-1.85)	5.92 (10.55)	6.25 (-1.94)
T50	9.04 (-1.53)	10.4 (-1.27)	10.52 (-1.24)	11.34 (-0.95)
T100	11.23 (-1.08)	12.13 (-0.74)	12.21 (-0.73)	12.81 (-0.71)
T500	14.53 (-0.67)	15.09 (-0.62)	14.94 (-2.29)	15.8 (16.18)

The damage costs for the multi-hazard flood are presented in the table below. The important aspects are the following:

- Exponential Growth in High-Frequency Risk (T1): While historically T1 events caused negligible damage (near 0 M€), they are projected to reach 0.17 M€ by 2100. This represents a 103.45% increase over single-hazard projections, indicating that frequent, low-magnitude floods will become a substantial financial burden.
- Peak Infrastructure Stress (T500): Maximum repair times reach a peak of 11.40 days in the 2071–2100 period. The associated damage cost for these extreme events rises to 11.4 M€, a 13.88% increase compared to single-hazard assessments.
- Intermediate Period Resilience: For T50 and T100 events, the "single hazard difference" remains relatively low or even negative (e.g., -0.78% for T50 in 2071–2100). This indicates that

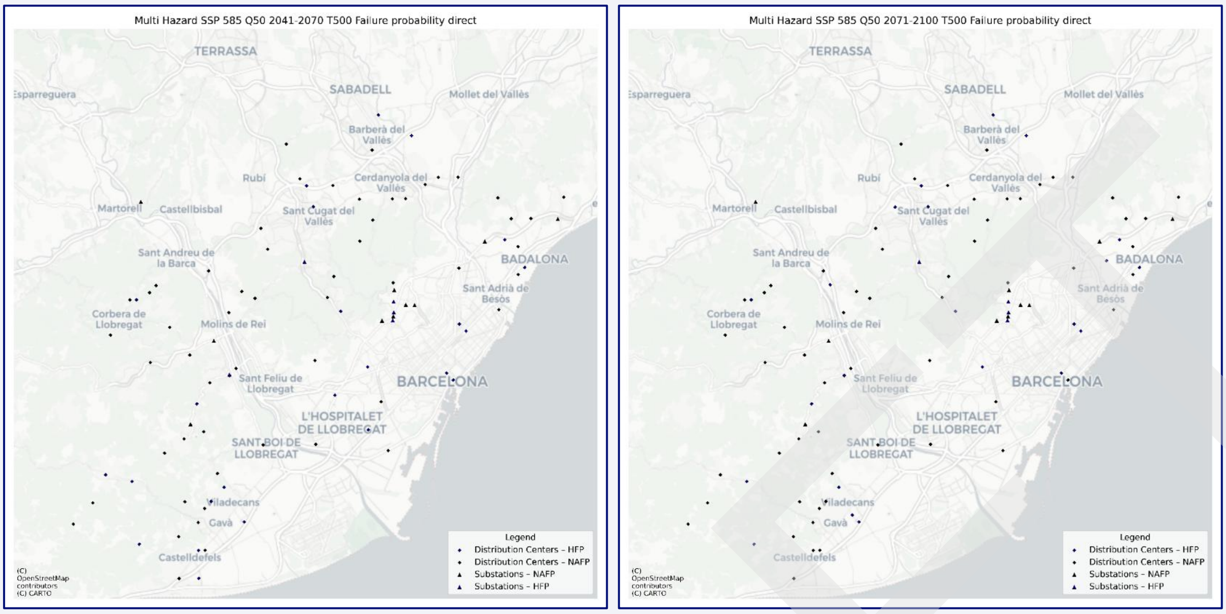
for mid-range return periods, infrastructure damage is more predictable and less influenced by compound hazard interaction.

Return period	Damage Cost (M€) Single hazard difference (%)			
	Climate change projection period			
	Historic	2015-2040	2041-2070	2071-2100
T1	0 (-40)	0.13 (43.45)	0.14 (49.53)	0.17 (103.45)
T10	2.62 (-2.71)	2.86 (0.37)	2.99 (26.44)	3.14 (3.72)
T50	4.5 (-0.27)	5.24 (-1.83)	5.41 (-1.63)	6 (-0.78)
T100	6.32 (0.25)	6.99 (4.36)	7.16 (4.49)	7.9 (5.12)
T500	10.01 (2.17)	10.52 (4.53)	10.03 (-4.28)	11.4 (13.88)

These results demonstrate that the Barcelona Metropolitan Area's electrical grid faces a compounded resilience deficit over the century. The primary driver of future risk is the non-linear combined effect of multi-hazard interactions, which becomes critically evident in the 2071–2100 SSP5-8.5 projection. During this period, compound flooding elevates both mean and maximum repair times significantly above historic baselines, with a "multi-hazard penalty" reaching 20.37% for high-frequency events and 16.18% for catastrophic T500 scenarios.

From a financial perspective, the transformation of T1 (high-frequency) events is the most alarming trend. The analyzed events have shifted from negligible operational inconveniences to significant contributors to damage, with costs increasing by over 100% due to compound hazard effects. Consequently, traditional single-hazard risk assessments will fail to capture the true scale of Direct Damage (CAPEX) and subsequent Business Costs resulting from extended downtime. These findings mandate a shift toward multi-hazard adaptation strategies, as projected recovery timelines toward 2100 are likely to exceed current emergency response capacities and auxiliary power resources.

The following images illustrate the difference between T500 for 2041-2070 and T500 for 2071-2100. In this case, there is a slight increase in the affected installation, as shown in the tables above.



5.2.6 Indirect economic damages of multi-hazard floods

Multi-hazard risk assessment of COMPOUND FLOODS on INDIRECT ECONOMIC DAMAGE

Impact assessment methodology

The methodology used for this multi-hazard risk assessment is the same as presented in Section 5.1.8. The difference between the scenarios concerns the hazard assessment dimension as explained in Sections 4.2.1 (AMB CS hazard assessment model) and 4.3.1 (AMB CS risk assessment scenarios).

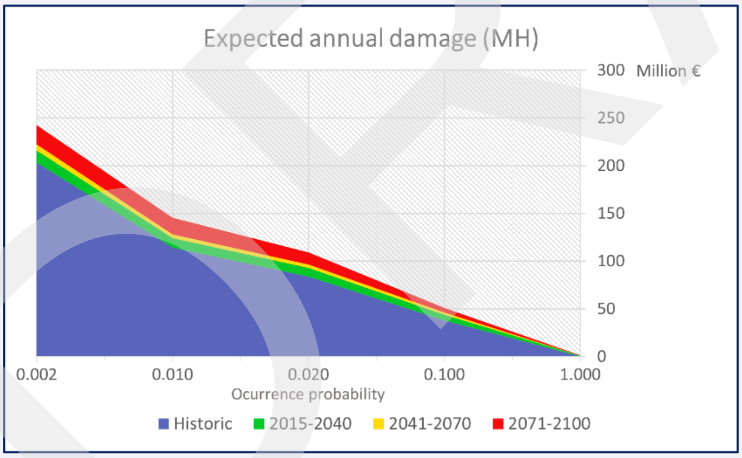
Impact assessment results

The results show that considering multiple hazards leads to a systematic increase in indirect economic damages across all return periods and time horizons, compared to the single-hazard assessment. Indirect losses rise both with flood severity and over time, reflecting the compounded effects of interacting hazards on economic activity within the AMB.

	Indirect Economic damage of pluvial floods (and percentage of increase with respect to previous event)					
Projection Period	**T1**	**T10**	**T50**	**T100**	**T500**	**Expected annual damage**
Historic	10.989,47	37.811.709,08	83.797.625,20	114.107.145,52	203.159.035,33	24.143.176
2015-2040	871.664,72	43.779.943,80 (+15.78%)	92.779.399,13 (+10,72%)	124.152.507,61 (+8,80%)	215.716.315,83 (+6.18%)	27.999.732 (+15,97%)
2041-2070	974.157,27	46.259.024,82 (+5.66%)	96.406.919,01 (+3.91%)	128.135.251,18 (+3,21%)	222.151.710,80 (+2,98%)	29.485.428 (+5.31%)
2071-2100	1.501.875,81	51.023.508,31 (+10.30%)	108.906.460 (+12,97%)	145.378.990,6 (+13.46%)	242.424.866,7 (9,13%)	32.856.264 (+11.43%)

For the Historical period, total indirect damages reached around €37.8 million for T10 events and approximately €203.2 million for T500 events, with an Estimated Annual Damage (EAD) of around €24.1 million.

In the 2015–2040 horizon, total indirect losses increased to approximately €43.8 million (T10) and €215.7 million (T500), corresponding to an EAD of about €28.0 million, which represents an increase of 15.97% compared to the Historical period. This growing pattern continues into 2041–2070, where indirect damages reach €46.3 million (T10) and €222.2 million (T500), and the EAD rises to approximately €29.5 million. The 2071–2100 period represents the most adverse conditions under the multi-hazard framework. In this horizon, indirect damages reach €51.0 million for T10 events and exceed €242.4 million for T500 events, while the EAD increases to approximately €32.9 million, representing an overall increase of 11.43% compared to the previous period.



Overall, the evolution of EAD values from the Historical period to the end of the century indicates a progressive intensification of long-term indirect flood risk, driven by increasing direct damages and their amplified propagation through the metropolitan economy when multiple hazards are considered simultaneously.

As in the single-hazard case, indirect impacts are unevenly distributed across economic sectors, but their absolute magnitude is consistently higher.

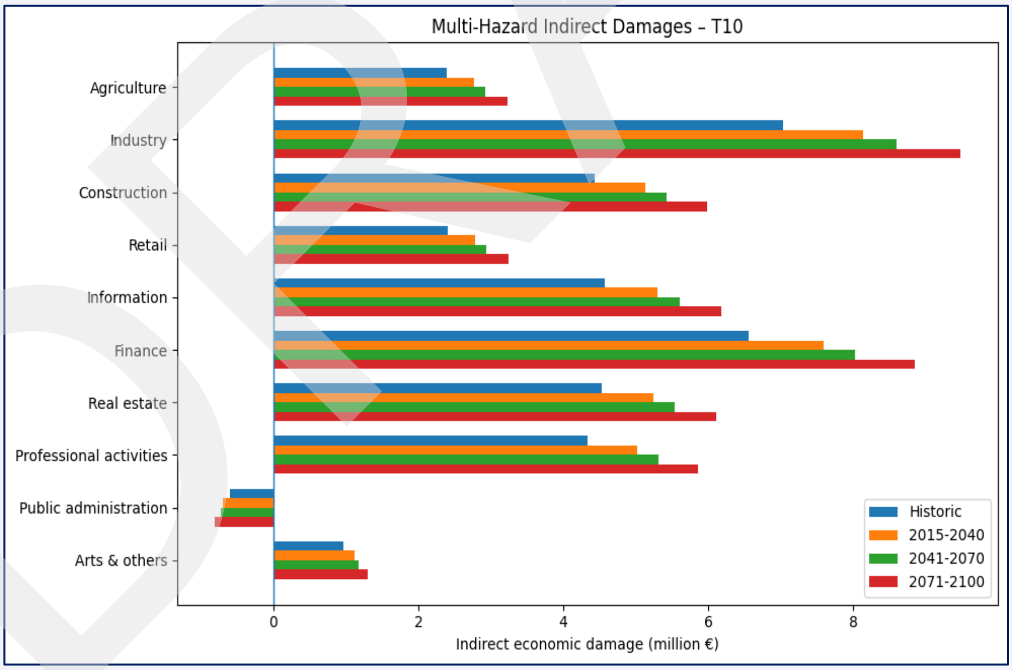
Across all periods and return levels, industry and financial activities remain the most affected sectors, jointly accounting for around 35–40% of total indirect damages. For extreme events (T500) in the 2071–2100 period, indirect losses in these two sectors alone reach approximately €45.0 million (Industry) and €42.1 million (Finance), underlining their strong interdependencies and high sensitivity to cascading disruptions triggered by compound hazards.

A second group of sectors—including construction, real estate, professional activities, and information and communication services—also experiences substantial indirect losses. For T500 events in the 2071–2100 horizon, losses in these sectors range between approximately €27.8 million and €29.3 million, showing a clear escalation with both hazard severity and time.

Agriculture and retail show lower absolute indirect damages compared to other sectors, reflecting their relatively smaller weight in the metropolitan economy. Nevertheless, under the multi-hazard framework, indirect losses in these sectors still reach around €15.3–15.4 million for extreme events in the later periods, indicating a non-negligible sensitivity to compound disruptions.

The public administration sector continues to show a negative contribution to indirect damages across all scenarios and return periods. As in the single-hazard assessment, this outcome results from the econometric specification used to estimate sectoral sensitivities and should be interpreted as a lower relative exposure to business interruption effects rather than as an actual economic benefit.

Finally, arts and other services represent a smaller but steadily increasing share of indirect damages. Under extreme multi-hazard scenarios, losses in this group reach more than €6.1 million for T500 events by the end of the century.



5.2.7 Cascading effects related to the multi hazard

Cascading effects to multi hazard on ELECTRICITY

Cascading risk assessment methodology

The methodology to assess the cascading effect on multi-hazard is the same as exposed in section 5.1.10.

Cascading effect results

Using the results of the risk assessment on the electricity of the AMB in the same scenario. The following table shows information about the consumers and electrical assets affected by the cascading effects, followed by the highlights of each table:

Return period	Affected consumers Single hazard difference (%)			
	Climate change projection period			
	Historic	2015-2040	2041-2070	2071-2100
T1	0 (0)	0 (0)	0 (0)	0 (0)
T10	1175 (0.17)	1175 (0.17)	1175 (20.27)	1181 (-20.2)
T50	5227 (-11.09)	6496 (0.12)	6496 (-5.25)	7256 (0.11)
T100	7369 (0.38)	7456 (0.38)	7456 (0.38)	8231 (8.16)
T500	14821 (0.32)	14945 (0.34)	10808 (-27.45)	17022 (42.11)

- Extreme Scalability in Late-Century Events (T500): The most significant impact occurs in the 2071–2100 horizon for T500 events, where affected consumers reach 17,022. This represents a 42.11% increase compared to single-hazard projections, highlighting how compound flooding disproportionately expands the footprint of service disruption.
- Intermediate Return Period Growth: For T100 events, the number of affected consumers rises from 7,369 (Historic) to 8,231 (2071–2100), with an 8.16% multi-hazard penalty at the end of the century.
- T10 Paradox: Interestingly, while the absolute number of affected consumers for T10 increases slightly (from 1,175 to 1,181), the single hazard difference for the 2071–2100 period is -20.2%, suggesting that at this specific frequency, the single-hazard separation could over-allocate consumers compared to the integrated multi-hazard intersection.

Return period	Affected installations only cascading			
	Climate change projection period			
	Historic	2015-2040	2041-2070	2071-2100
T1	0	0	0	0
T10	0	0	0	0
T50	1	1	1	0
T100	0	0	0	2
T500	19	17	1	17

- Systemic Increase in Asset Exposure: The total number of affected installations for T500 events increases from 44 (Historic) to 51 (2071–2100). The multi-hazard interaction results in a 10.87% increase in exposure relative to single-hazard assessments in the final period.
- Critical Thresholds for T100: For T100 events, the number of damaged installations grows from 30 to 34 by 2100, with a 13.33% difference attributable to multi-hazard synergy.
- Low-Frequency Resilience: T1 events show zero affected installations across all climate horizons, indicating that the network's physical hardening or elevation is currently sufficient to withstand very high-frequency flood events without structural failure.

Return period	Affected installations total Single hazard difference (%)			
	Climate change projection period			
	Historic	2015-2040	2041-2070	2071-2100
T1	0 (0)	0 (0)	0 (0)	0 (0)
T10	10 (11.11)	10 (11.11)	10 (25)	11 (10)
T50	16 (-15.79)	23 (9.52)	23 (4.55)	27 (8)
T100	30 (11.11)	32 (10.34)	32 (10.34)	34 (13.33)
T500	44 (2.33)	47 (6.82)	45 (0)	51 (10.87)

- Dominance of T500 Cascades: Cascading failures are almost exclusively linked to extreme T500 events. In the 2071–2100 period, 17 installations are projected to fail due to cascading effects.

- Non-Linear Vulnerability: There is a notable "dip" in the 2041–2070 period where only 1 installation fails via cascade for T500, compared to 19 in the Historic period. This may reflect a shift in flood polygons that bypasses critical "hub" nodes during that specific timeframe.
- Emergent Cascades in T100: By the 2071–2100 period, the model identifies 2 installations failing via cascade for T100 events—a phenomenon not seen in earlier climate horizons, signaling that the grid's operational margin of safety is eroding.

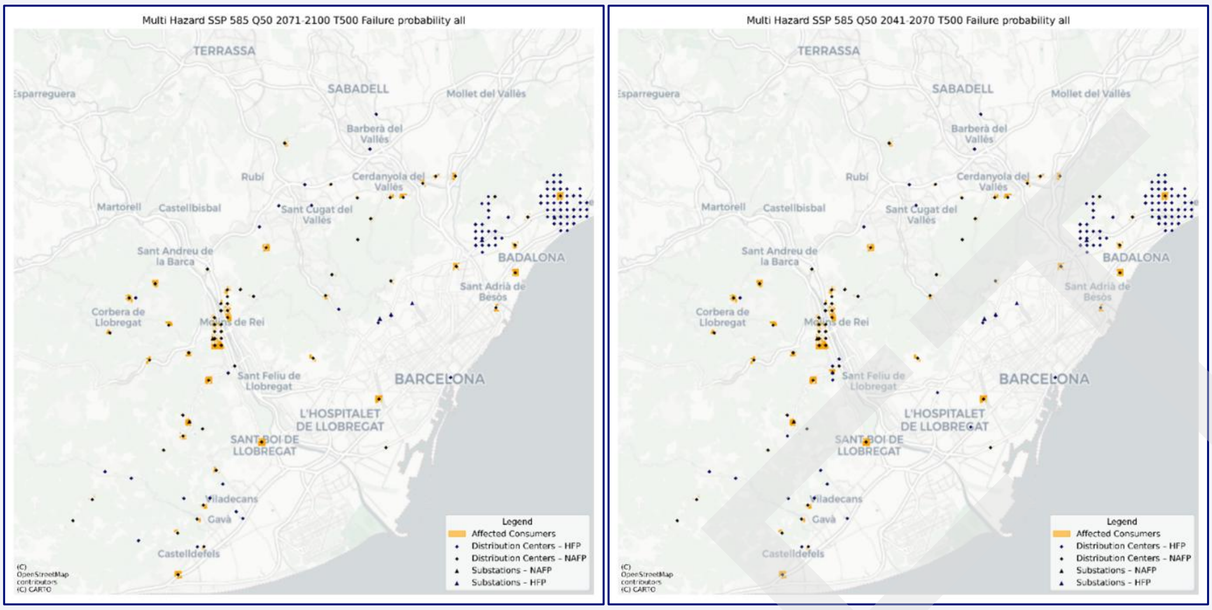
Return period	Energy None Supplied Cost (k€) Single hazard difference (%)			
	Climate change projection period			
	Historic	2015-2040	2041-2070	2071-2100
T1	0.01 (-56.04)	9.50 (15.45)	10.47 (17.19)	10.78 (24.53)
T10	97.74 (-6.87)	107.11 (-1.64)	110.64 (12.4)	115.33 (2.38)
T50	144.98 (-5.51)	155.43 (-6.16)	159.14 (-7.47)	168.24 (-6.84)
T100	176.78 (-7.67)	191.78 (5.48)	194.79 (5.87)	208.65 (6.4)
T500	240.15 (5.71)	250.52 (8.64)	231.95 (-3.3)	265.04 (15.9)

- Acceleration of High-Frequency Impact (T1): While historically negligible, the ENS cost for T1 events surges to 10.78 k€ by 2100. The "Single hazard difference" grows significantly, reaching 24.53%, indicating that high-frequency events will cause disproportionately more economic disruption under multi-hazard conditions.
- Peak Economic Risk (T500): The cost for catastrophic T500 events rises from 240.15 k€ (Historic) to 265.04 k€ (2071–2100). In the final period, the multi-hazard synergy adds a 15.9% penalty compared to single-hazard models.
- Consistency in Intermediate Risks: For T50 events, the ENS cost remains consistently higher in the multi-hazard model than in single-hazard models, though the difference remains negative (approx. -6.84% in 2100), suggesting that coastal or pluvial models individually might overestimate ENS for moderate return periods.

Return period	Auxiliar Generation Cost (M€) Single hazard difference (%)			
	Climate change projection period			
	Historic	2015-2040	2041-2070	2071-2100
T1	0 (0)	0.15 (27.12)	0.17 (30.5)	0.17 (47.59)
T10	1.93 (-9.78)	2.11 (-5.28)	2.18 (9.59)	2.3 (-2.79)
T50	3.04 (-11.68)	3.37 (-15.62)	3.48 (-19.19)	3.77 (-17.45)
T100	3.91 (-15.24)	4.44 (-7.48)	4.51 (-7.62)	4.88 (-6.32)
T500	5.98 (-1.95)	6.26 (0)	5.85 (-9.87)	6.72 (8.72)

- Surge in Mitigation Costs for T1: Similar to ENS, the cost of auxiliary generation for T1 events jumps from 0 to 0.17 M€ by 2100. The multi-hazard interaction adds a 47.59% premium to these costs, signaling a massive increase in the logistics of maintaining high-frequency grid resilience.
- Stabilization of Large-Scale Mitigation: For T100 events, the AGC reaches 4.88 M€ by 2100. Interestingly, the multi-hazard model shows lower costs than the single-hazard baseline (-6.32%), which may indicate that the spatial intersection of hazards reduces the "redundant" deployment of auxiliary units compared to treating coastal and pluvial risks separately.
- Correlation with Asset Failure: The AGC strictly follows the physical failure of installations, peaking at nearly 5 M€ for return periods where primary substations are compromised.

The following images illustrate the difference between T500 for 2041-2070 and T500 for 2071-2100. In this case, there is a slight increase in the affected installation, as shown in the tables above.



5.3 Adaptation scenario risk assessment

The methodologies used for risk assessment of the adaptation scenario results were the same as those presented in Section 5.1.3. The difference among scenarios concerns the hazard assessment dimension. The flood hazard model, explained in Section 4.2.1 (AMB CS hazard assessment model), was further developed to incorporate the adaptation measures in Section 4.4.1. Overall, it reflects a scenario where the AMB has taken major action to improve its resilience against floods by implementing NbS and other runoff reduction actions.

Importantly, all simulations reported here consider the same hazard drivers as the multi-hazard scenarios: coincident precipitation and storm surge conditions. Therefore, the evaluation of the effectiveness of the mentioned measure is determined by comparing the impact results of the multi-hazard with the adaptation scenarios.

5.3.1 Adaptation scenario risk for risk receptor people

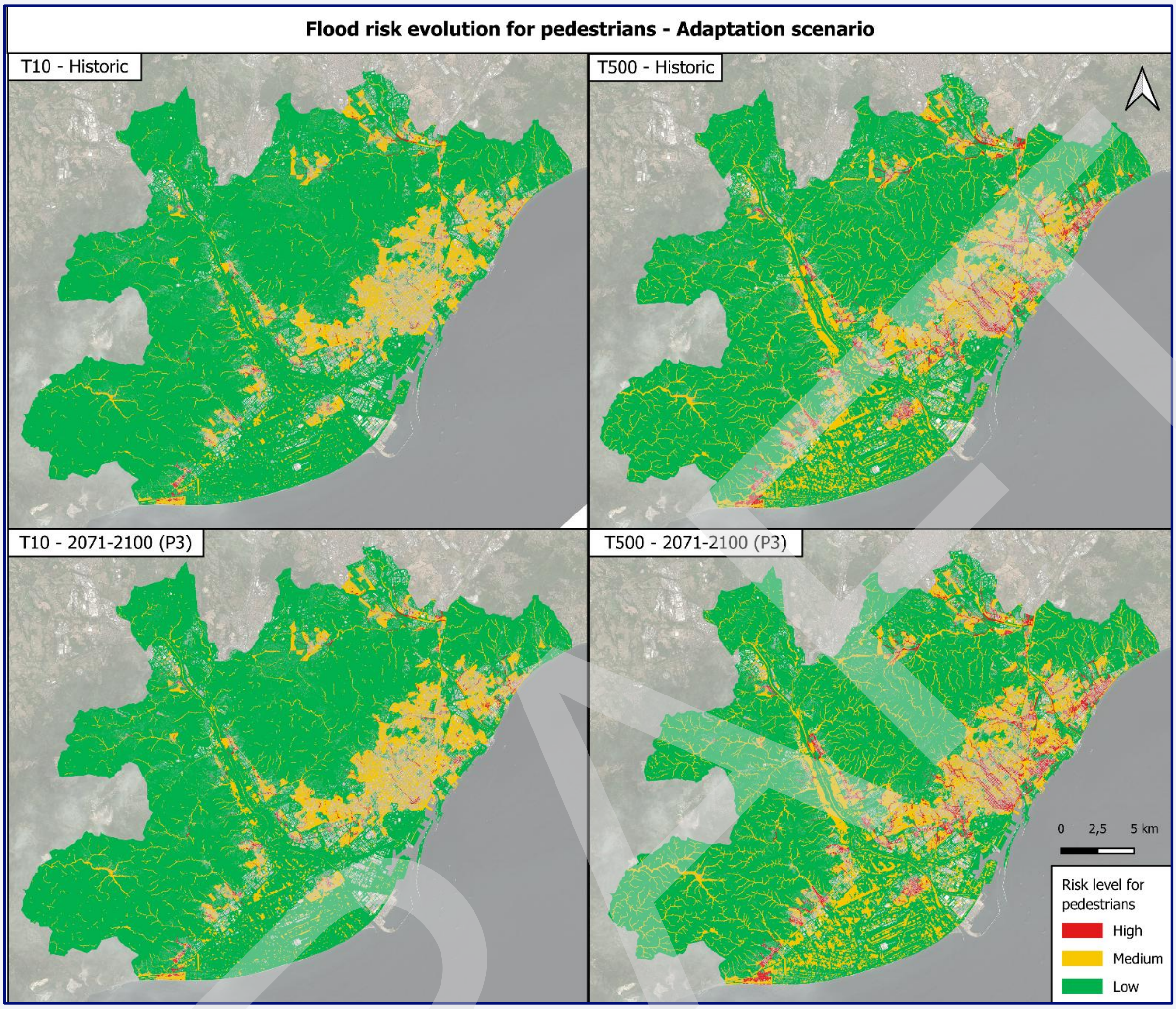
Adaptation scenario risk assessment of COMPOUND FLOODS on PEOPLE
Adaptation scenario risk assessment methodology
The methodology used for this multi-hazard risk assessment is the same as presented in Section 5.1.1. The difference between the scenarios concerns the hazard assessment dimension as explained in Sections 4.2.1 (AMB CS hazard assessment model) and 4.3.1 (AMB CS risk assessment scenarios). Additionally, the hazard model for this assessment considers the adaptation measures in section 4.4.1.

Adaptation scenario risk assessment results

The results in the table below show the total area identified as high risk for pedestrians for the multiple simulations done for the adaptation section, considering the multi-hazard conditions (coincident precipitation and storm surge). The same trend is shown as in the previous scenarios (single-hazard and multi-hazard). The high-risk areas increase along with growing return periods and climate change projections. If compared with section 5.2.1, it can be observed that the growth rates are similar to the multi-hazard scenario. With respect to the historic scenario considering adaptation measures, growths of 5.7 to 14.9% are observed for the Period 1 simulations, 7.2 to 20.8% for Period 2, and 16.0 to 27.9 %for Period 3. The largest increase is observed in the lower return period.

	Area of HIGH flood risk on pedestrians for the return periods considered (ha) (and percentage of increase with respect to historic event)				
Projection Period	**T1**	**T10**	**T50**	**T100**	**T500**
Historic	1.68	449.67	858.99	1125.20	1686.98
2015-2040	18.76	516.88 (+14.9%)	958.47 (+11.6%)	1198.65 (+6.5%)	1782.63 (+5.7%)
2041-2070	20.22	543.37 (+20.8%)	978.50 (+13.9%)	1214.66 (+8.0%)	1809.08 (+7.2%)
2071-2100	27.86	575.15 (+27.9%)	1083.58 (+26.1%)	1347.11 (+19.7%)	1956.74 (+16.0%)

The spatial distribution of medium and high-risk areas is very similar to the multi-hazard simulations. Risk areas representation for T10 (Historic and Period 3) and T500 (Historic and Period 3) shows that medium and high-risk concentrate in the preferential water paths. In particular, high-risk areas are located in the intersection between flood-prone urban areas and highly populated areas, typically in the urban centers of the municipalities in the AMB.

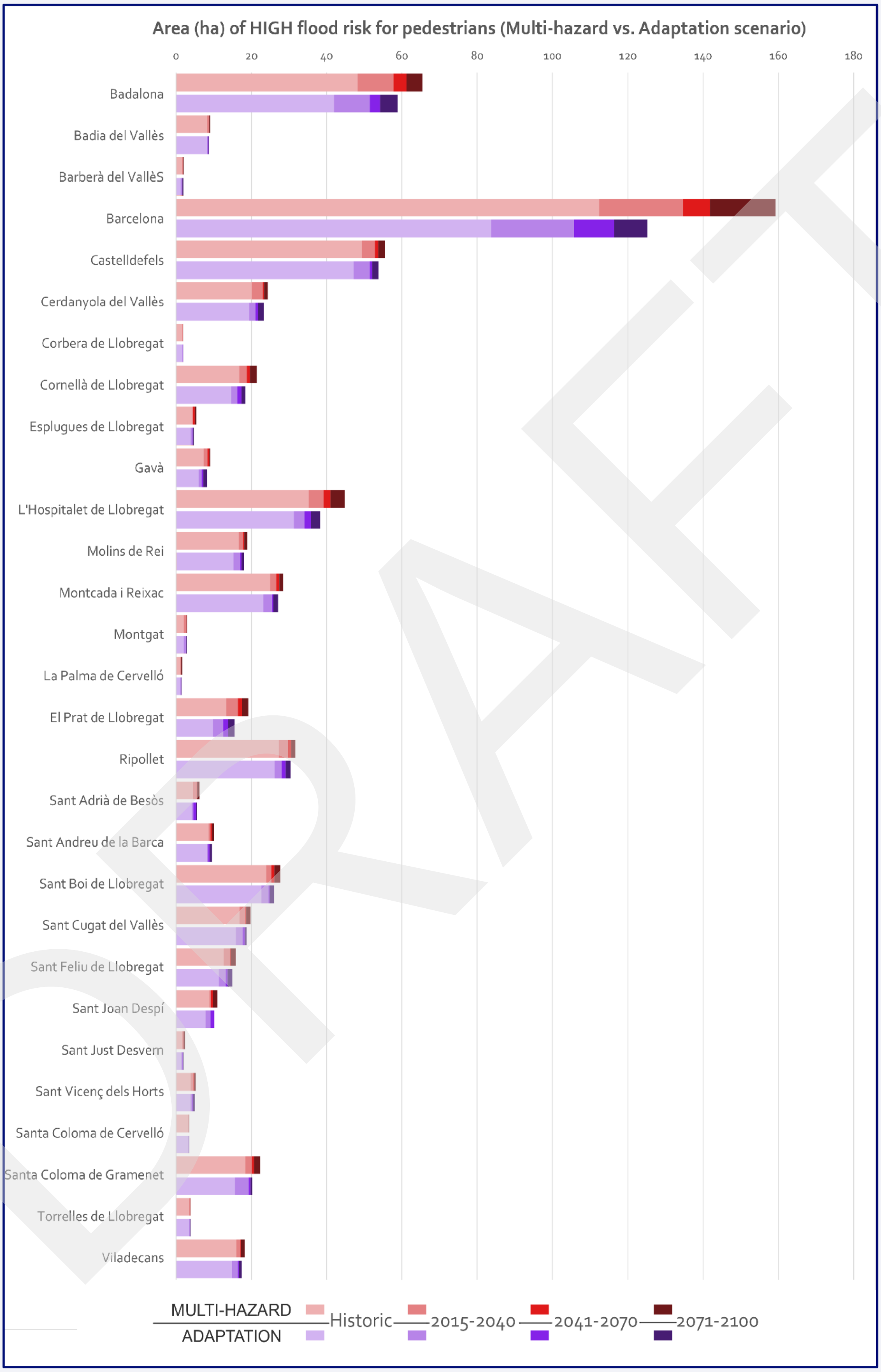


Comparison between the multi-hazard and the adaptation scenarios

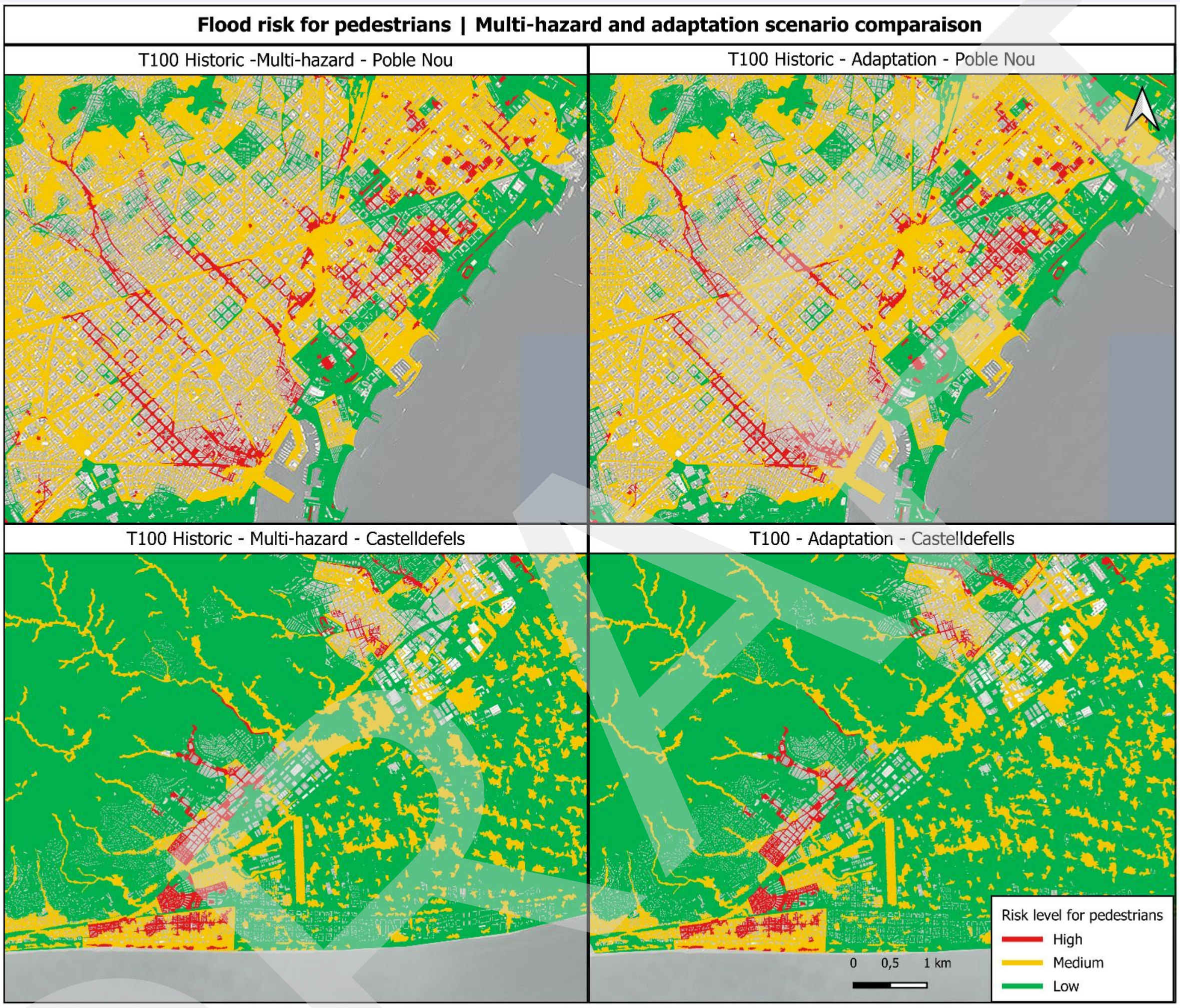
The comparison between the total high-risk areas in the multi-hazard and adaptation scenarios proves the effectiveness of the adaptation strategy against floods proposed for the AMB CS. The risk reduction percentages are 17 to 19% for T1 events, 10 to 12% for T10, 9 to 10% for T50, 7 to 9% for T100, and 0 to 6% for T500. The explanation for this regular decrease in risk reduction is the following. The adaptation measures proposed, in particular green roofs, are designed to mitigate the effect of ordinary rain events (up to T10). Porous pavements and bioretention areas can potentially be effective up to some point for larger rain events. If other measures specifically designed to reduce the impacts of extreme rain events, like T100 and T500, were introduced in the 1D/2D model, results would show greater reduction of high-risk areas for these events.

Return period	Modelling scenario	High-risk area for pedestrians (ha)			
		Climate change projection period			
		Historic	2015-2040	2041-2017	2071-2100
T1	Multi-hazard scenario	1.69	22.73	23.99	34.20
	Adaptation scenario	1.68	18.76	20.22	27.86
	Difference	-1%	-17%	-16%	-19%
T10	Multi-hazard scenario	513.02	579.34	601.15	647.06
	Adaptation scenario	449.67	516.88	543.37	575.15
	Difference	-12%	-11%	-10%	-11%
T50	Multi-hazard scenario	952.08	1042.69	1085.16	1185.93
	Adaptation scenario	858.99	958.47	978.50	1083.58
	Difference	-10%	-8%	-10%	-9%
T100	Multi-hazard scenario	1208.21	1299.32	1333.94	1463.34
	Adaptation scenario	1125.20	1198.65	1214.66	1347.11
	Difference	-7%	-8%	-9%	-8%
T500	Multi-hazard scenario	1798.78	1916.64	1955.57	1956.82
	Adaptation scenario	1686.98	1782.63	1809.08	1956.74
	Difference	-6%	-7%	-7%	0%

It can be observed in the graph below that the risk reduction in the municipalities of the AMB is proportional to the high-risk obtained in the multi-hazard simulations. Thus, the municipalities with a larger risk in the multi-hazard scenario have a higher risk reduction in the adaptation case. This is consistent with the fact that the adaptation measures are distributed across the AMB in proportion to the size of each municipality.


Area (ha) of HIGH flood risk for pedestrians (Multi-hazard vs. Adaptation scenario)
0
20
40
60
80
100
120
140
160
180
Badalona
Badia del Vallès
Barberà del VallèS
Barcelona
Castelldefels
Cerdanyola del Vallès
Corbera de Llobregat
Cornellà de Llobregat
Esplugues de Llobregat
Gavà
L'Hospitalet de Llobregat
Molins de Rei
Montcada i Reixac
Montgat
La Palma de Cervelló
El Prat de Llobregat
Ripollet
Sant Adrià de Besòs
Sant Andreu de la Barca
Sant Boi de Llobregat
Sant Cugat del Vallès
Sant Feliu de Llobregat
Sant Joan Despí
Sant Just Desvern
Sant Vicenç dels Horts
Santa Coloma de Cervelló
Santa Coloma de Gramenet
Torrelles de Llobregat
Viladecans
MULTI-HAZARD
ADAPTATION
Historic
2015-2040
2041-2070
2071-2100

In consistency with the previous graph. The maps below show that the reduction of risk areas in two locations, particularly affected by combined floods, is diffuse. The effect of the adaptation measures is not specifically located in the high-risk areas, but it affects the whole urban areas.



5.3.2 Adaptation scenario risk for risk receptor transport

Multi-hazard risk assessment of COMPOUND FLOODS on TRANSPORT

Adaptation scenario risk assessment methodology

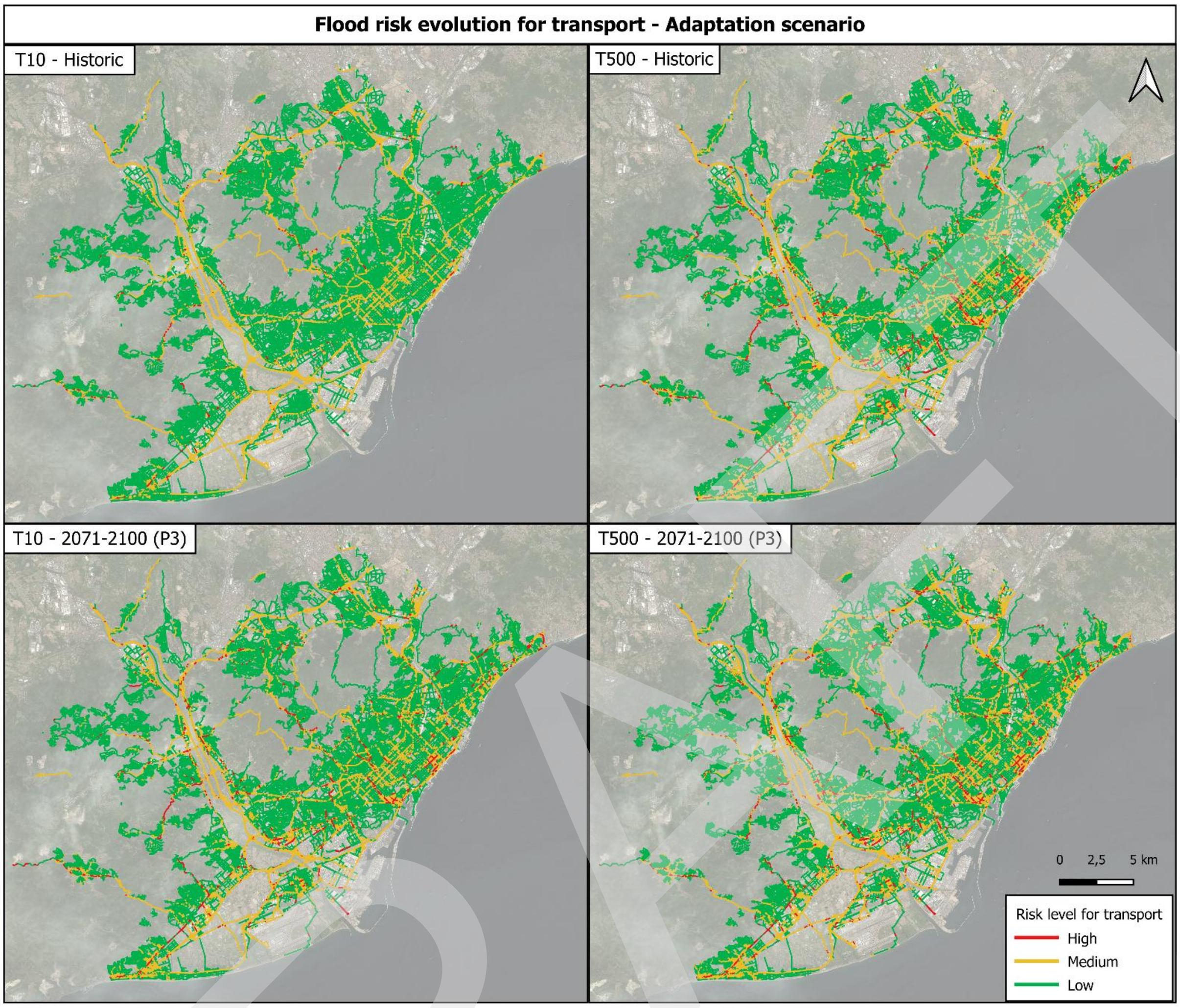
The methodology used for this multi-hazard risk assessment is the same as presented in Section 5.1.2. The difference between the scenarios concerns the hazard assessment dimension as explained in Sections 4.2.1 (AMB CS hazard assessment model) and 4.3.1 (AMB CS risk assessment scenarios). Additionally, the hazard model for this assessment considers the adaptation measures in section 4.4.1.

Adaptation scenario risk assessment results

The adaptation scenario flood results in the following table show the total area classified as high risk for pedestrians for all the simulations run. Similar to the previous scenarios, this data indicates that the risk for pedestrians grows alongside rainfall intensity and the climate change scenarios. With respect to the historic baseline simulation, growths of 6.6 to 13.5% are observed for the Period 1 simulations, 8.8 to 20.4% for Period 2, and 20.7 to 28.1% for Period 3. In consistency with the previous sections, the largest increase is observed in the lower return period events.

	Area of HIGH flood risk on transport for the return periods considered (km) (and percentage of increase with respect to historic event)				
Projection Period	**T1**	**T10**	**T50**	**T100**	**T500**
Historic	0.08	53.73	109.23	153.76	252.23
2015-2040	3.37	60.97 (+13.5%)	123.07 (+12.7%)	165.58 (+7.7%)	268.84 (+6.6%)
2041-2070	3.65	64.71 (+20.4%)	127.73 (+16.9%)	168.13 (+9.3%)	274.40 (+8.8%)
2071-2100	4.48	68.81 (+28.1%)	145.83 (+33.5%)	187.27 (+21.8%)	304.36 (+20.7%)

The location of medium and high-risk areas follows the same pattern as in sections 5.1.2 (single-hazard risk for transport) and 5.2.2 (multi-hazard risk for transport). In particular, high-risk areas are located in the intersection between flood-prone urban areas and high traffic roads, typically in the urban centers and main roads and highways connecting the municipalities. Important floodable areas in peri-urban environments remain at medium risk due to the lower exposure and vulnerability metrics.

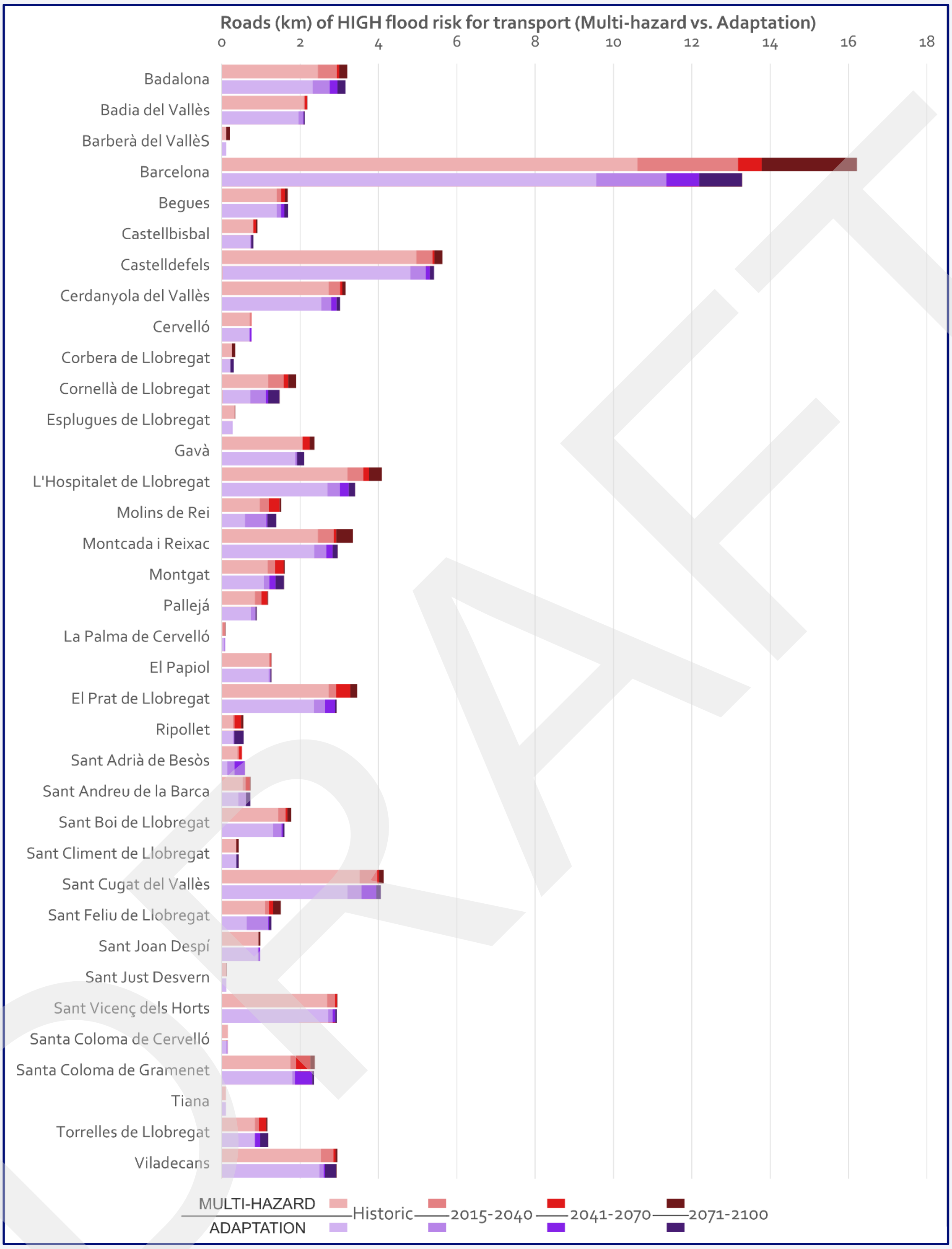


Comparison between the multi-hazard and the adaptation scenarios

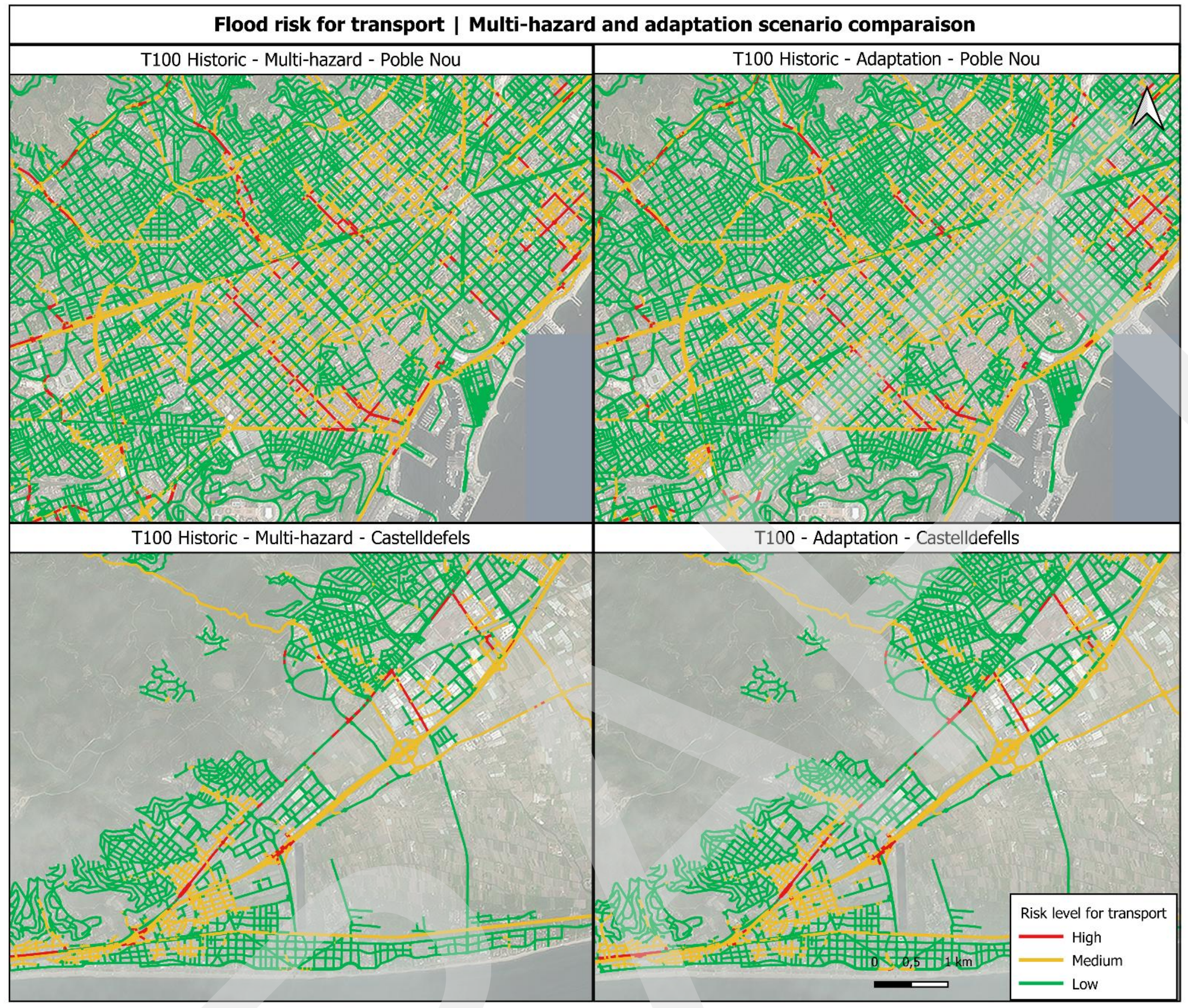
The following table compares the total extent of the high-risk transportation network between the multi-hazard and adaptation scenarios. The risk reduction percentages are 0 to 9% for T1 events, 9% for T10, 8 to 12% for T50, 6 to 10% for T100, and 1 to 9% for T500. It can be concluded that the risk reduction measures proposed are also effective for this risk receptor. However, unlike the case of risk for pedestrians, the risk reduction percentages are similar across all simulations.

Return period	Modelling scenario	High-risk roads for transport (Km)			
		Climate change projection period			
		Historic	2015-2040	2041-2017	2071-2100
T1	Multi-hazard scenario	0.08	3.84	3.91	4.95
	Adaptation scenario	0.08	3.37	3.65	4.48
	Difference	0%	-12%	-7%	-9%
T10	Multi-hazard scenario	59.05	66.70	70.42	75.79
	Adaptation scenario	53.73	60.97	64.71	68.81
	Difference	-9%	-9%	-8%	-9%
T50	Multi-hazard scenario	124.28	137.41	142.53	159.00
	Adaptation scenario	109.23	123.07	127.73	145.83
	Difference	-12%	-10%	-10%	-8%
T100	Multi-hazard scenario	163.88	177.45	183.57	207.18
	Adaptation scenario	153.76	165.58	168.13	187.27
	Difference	-6%	-7%	-8%	-10%
T500	Multi-hazard scenario	274.77	294.77	301.79	308.30
	Adaptation scenario	252.23	268.84	274.40	304.36
	Difference	-8%	-9%	-9%	-1%

At the municipal level, the risk reduction is split among municipalities in proportion to the km of roads and streets that they have. Thus, the highest risk reduction is observed in Barcelona, Hospitalet de Llobregat and Prat de Llobregat.



In consistency with the previous graph and the results in section 5.3.1 (adaptation scenario impact on pedestrians) the following maps show that the reduction of risk areas in two locations, particularly affected by combined floods, is diffuse and not targeted to the high-risk areas.



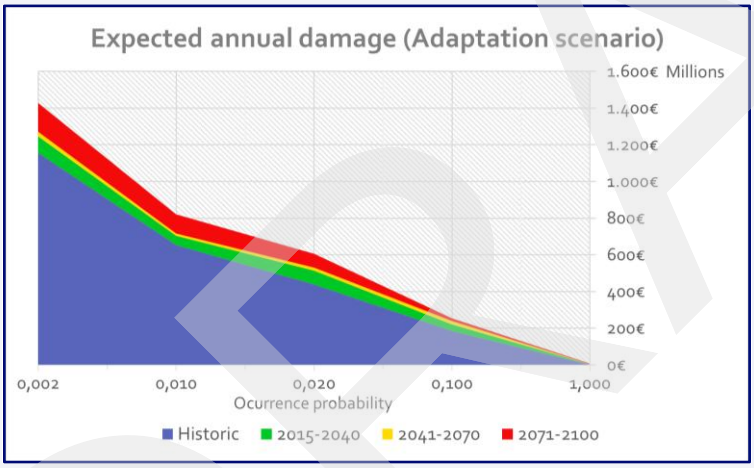
5.3.3 Adaptation scenario risk for risk receptor properties

Adaptation scenario risk assessment of COMPOUND FLOODS on PROPERTIES
Adaptation scenario risk assessment methodology
The methodology used for this adaptation risk assessment is the same as presented in Section 5.1.3. The difference between the scenarios concerns the hazard assessment dimension as explained in Sections 4.2.1 (AMB CS hazard assessment model) and 4.3.1 (AMB CS risk assessment scenarios). Additionally, the hazard model for this assessment considers the adaptation measures in section 4.4.1.

Adaptation scenario impact assessment results

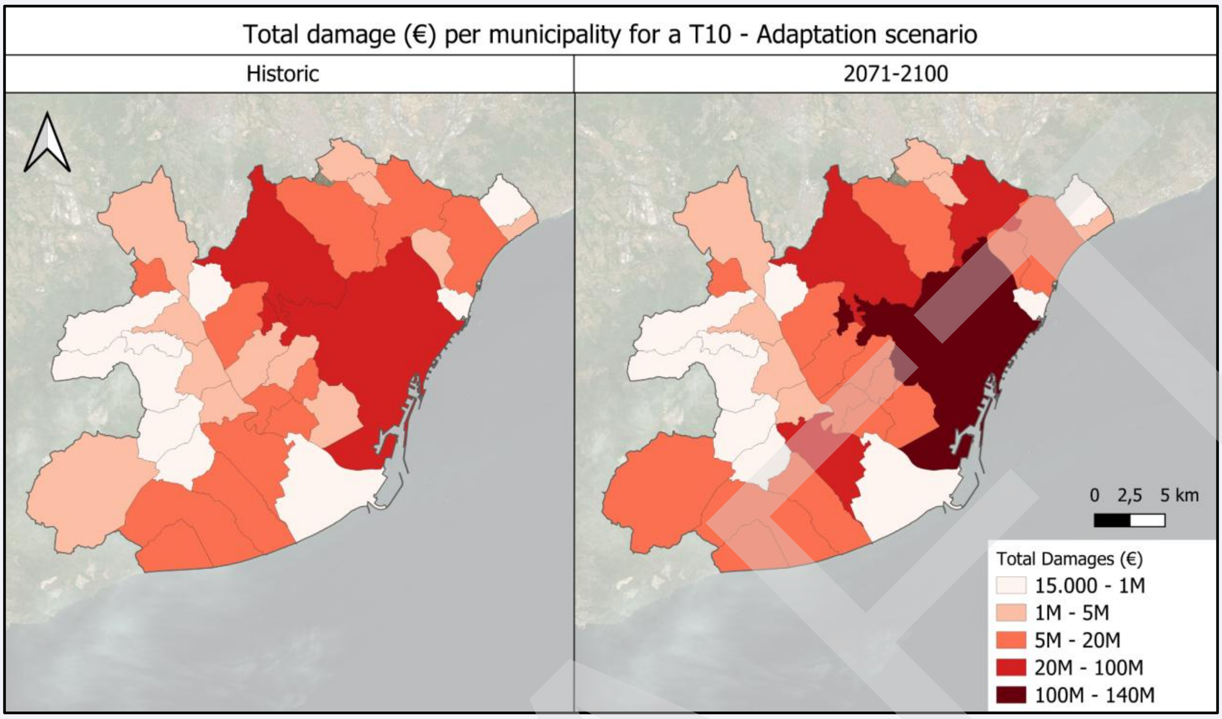
The economic impact of floods on buildings under the adaptation scenario is shown in the table below. Despite the resilience measures considered, the damages are still significant. For a T10 event, all future scenarios predict monetary impacts above 300M €, reaching up to 1,400M € for a T500 even in the long-term climate projection.

	Economic damage on properties for the return periods considered (and percentage of increase with respect to historic event)					
Projection Period	**T1**	**T10**	**T50**	**T100**	**T500**	**Expected annual damage**
Historic	131,275 €	185,487,143 €	438,367,854 €	653,518,527 €	1,155,837,773 €	121,179,345 €
2015-2040	4,032,424 €	221,004,694 € (+19.1%)	514,390,011 € (+17.3%)	703,850,503 € (+7.7%)	1,245,893,853 € (+7.8%)	144,572,671 € (+19.3%)
2041-2070	4,156,389 €	239,636,419 € (+29.2%)	529,595,780 € (+20.8%)	716,796,650 € (+9.7%)	1,271,322,504 € (+10.0%)	154,660,490 € (+27.6%)
2070-2100	6,558,059 €	254,102,444 € (+37.0%)	606,690,645 € (+38.4%)	821,692,851 € (+25.7%)	1,428,738,358 € (+23.6%)	167,872,592 € (+38.5%)



The expected annual damage rises to 144M € for the nearest future period, which means a 19.3% rise when compared to historic data. This increase is more than 38% when comparing the furthest period (2071-2100) to historic data, surpassing the 160M € mark.

This previously analyzed data is presented on the map below. It provides a comprehensive overview of property-related economic impacts across municipalities for a T10 event in the adaptation scenario. Historical records indicate that Barcelona and Sant Cugat del Valles are the only municipalities experiencing damages exceeding 20M €. When contrasting this historical context with projections for 2071-2100, a notable escalation in impact across most municipalities becomes evident, with two more territories (Sant Boi de Llobregat and Montcada i Reixac) projected to reach the 20M € threshold and Barcelona surpassing the 100M € threshold.



Comparison between the multi-hazard and the adaptation scenarios

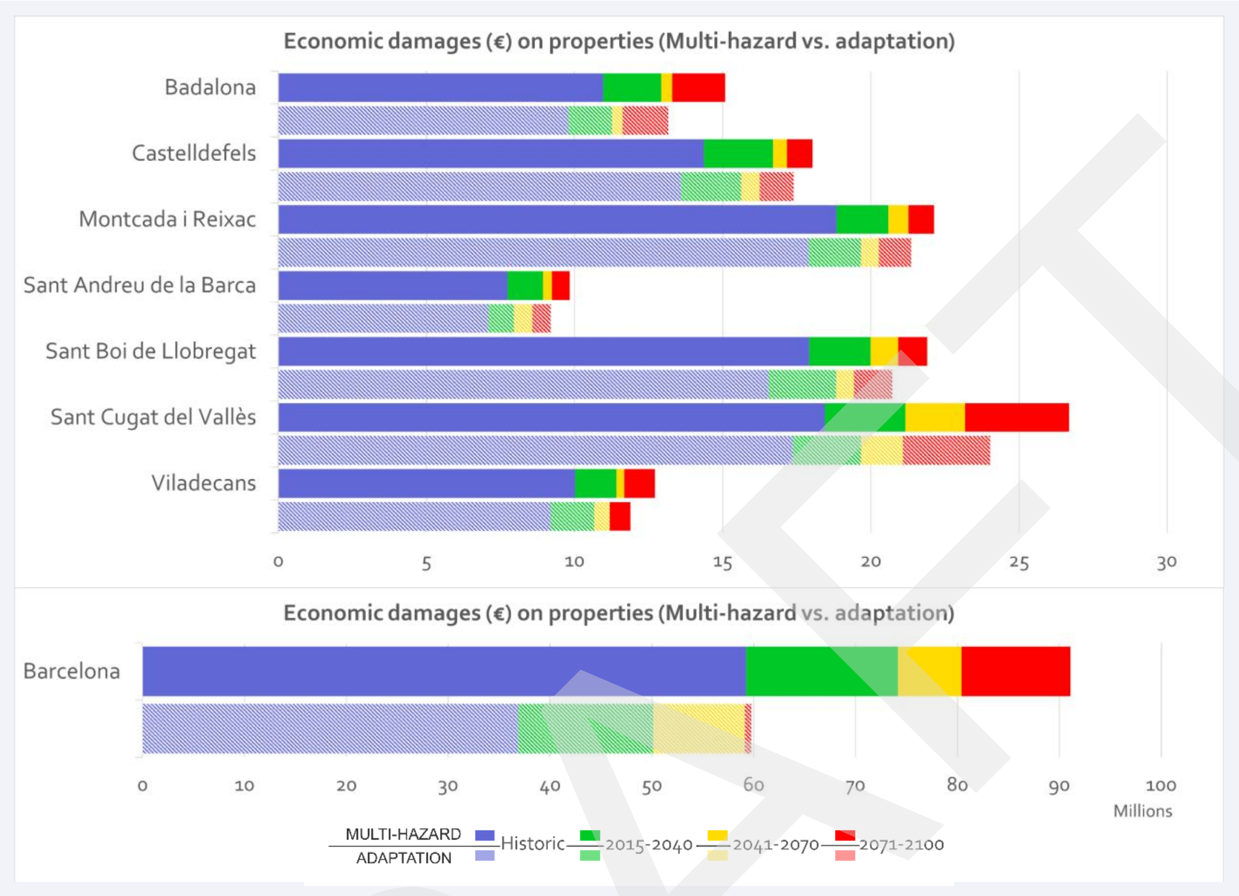
The economic damage results in the table below reflects that the impact-reduction capacity of the modelled adaptation measures in the AMB is effective. For all modelled scenarios and climate change projections, the associated damages are significantly reduced. The effect is particularly high for the T1 simulations. This situation is logical since an important part of the measures implemented are NbS. By definition, these urban elements have the capacity to reduce runoff for low return periods like T1 and T2. However, their water detention capacity is less significant for more intense events. Consequently, for T10 simulations, damage reduction ranges from 14 to 18% across projections. These percentages are reduced to 7 to 10% for the T500 storms. Regarding the EAD, it degrades in as similar as the economic damage of storm simulations.

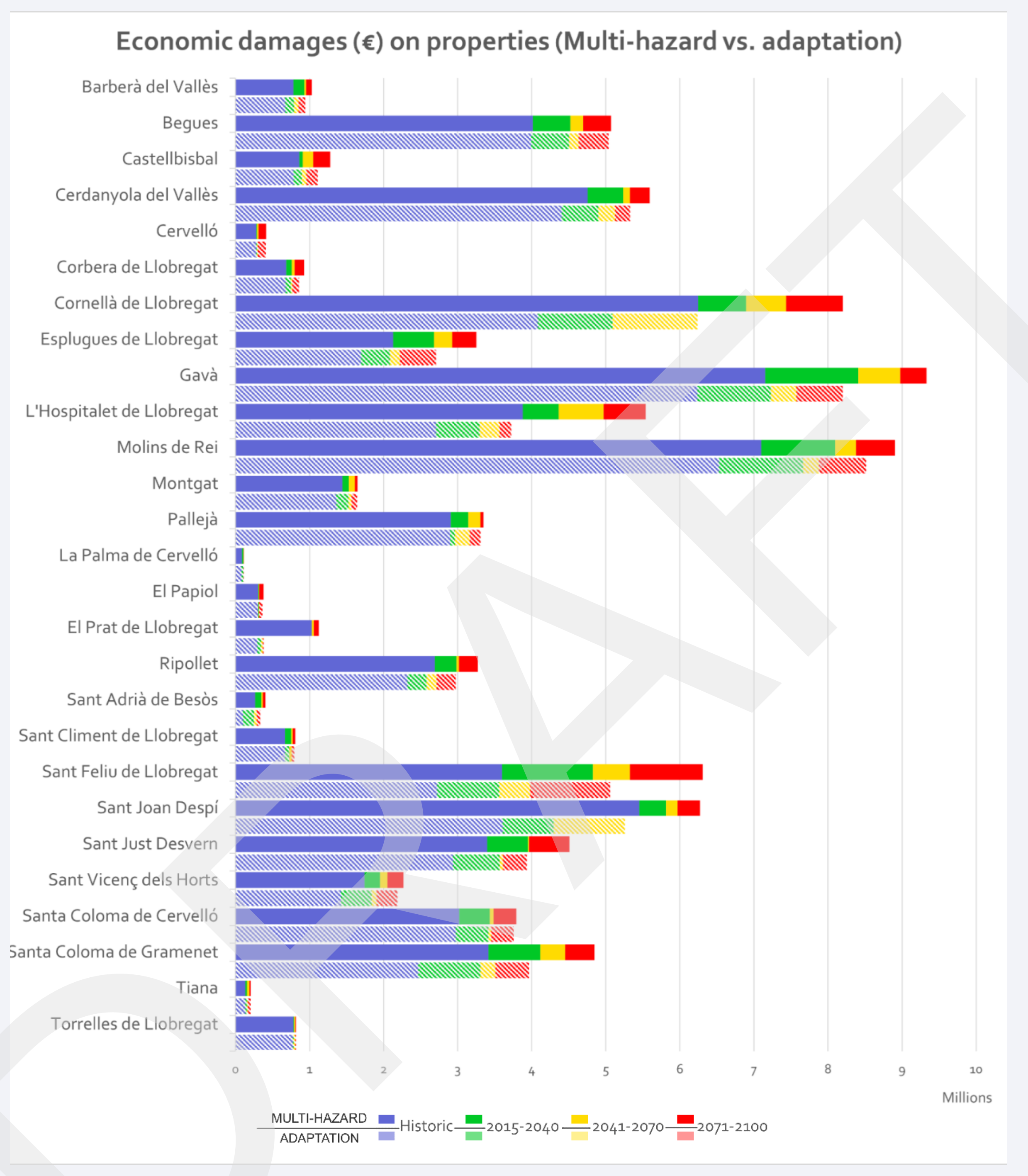
Given the fact that adaptation measures are, more or less, homogeneously distributed across the whole AMB, economic damage reduction is observed in all municipalities across all climate change projection periods. This pattern is consistent over time, even though absolute damages increase under future climate scenarios, particularly towards the end of the century.

Locally, the main impact reductions are observed in the municipalities experiencing the highest damages under the multi-hazard scenario (Barcelona, Badalona or Sant Cugat del Vallès). These municipalities concentrate a large share of exposed assets and built-up areas, which explains both their higher baseline damages and the greater absolute reductions achieved through adaptation. In terms of the proportion of economic damage reduction, the highest percentage reductions are observed in densely populated municipalities such as L'Hospitalet de Llobregat, Cornellà de Llobregat or Sant Boi de Llobregat. The reason is that these cases concentrate a larger building area and, consequently, a higher number of adaptation measures implemented within their domain.

Return period	Modelling scenario	Climate change projection period			
		Historic	2015-2040	2041-2017	2071-2100
T1	Multi-hazard scenario	0.14 M€	4.8 M€	5.2 M€	8.1 M€
	Adaptation scenario	0.13 M€	4.0 M€	4.2 M€	6.6 M€
	Damage increase	– 10%	– 16%	– 20%	– 19%
T10	Multi-hazard scenario	226.4 M€	264 M€	279.6 M€	306.9 M€
	Adaptation scenario	185.5 M€	221.0 M€	239.6 M€	254.1 M€
	Damage increase	– 18%	– 16%	– 14%	– 17%
T50	Multi-hazard scenario	516.9 M€	579.8 M€	603.3 M€	683.4 M€
	Adaptation scenario	438.4 M€	514.4 M€	529.6 M€	606.7 M€
	Damage increase	– 15%	– 11%	– 12%	– 11%
T100	Multi-hazard scenario	717.1 M€	785.8 M€	809.5 M€	919.8 M€
	Adaptation scenario	653.5 M€	703.9 M€	716.8 M€	821.7 M€
	Damage increase	– 9%	– 10%	– 11%	– 11%
T500	Multi-hazard scenario	1290.5 M€	1371.5 M€	1412.9 M€	1538.8 M€
	Adaptation scenario	1155.8 M€	1245.9 M€	1271.3 M€	1428.7 M€
	Damage increase	– 10%	– 9%	– 10%	– 7%
EAD	Multi-hazard scenario	145.9 M€	170.2 M€	179.4 M€	199.2 M€
	Adaptation scenario	121.2 M€	144.6 M€	154.7 M€	167,9 M€
	Damage increase	– 17%	– 15%	– 14%	– 16%

As a result, the relative effectiveness of adaptation is more visible. In contrast, municipalities where urbanized land is lower (e.g., Begues, Pallejà or Santa Coloma de Cervelló) show smaller absolute and relative reductions. Although adaptation measures are also implemented in these areas, the lower concentration of exposed assets limits the magnitude of the observable economic benefits.


Economic damages (€) on properties (Multi-hazard vs. adaptation)
Badalona
Castelldefels
Montcada i Reixac
Sant Andreu de la Barca
Sant Boi de Llobregat
Sant Cugat del Vallès
Viladecans
0
5
10
15
20
25
30
Economic damages (€) on properties (Multi-hazard vs. adaptation)
Barcelona
0
10
20
30
40
50
60
70
80
90
100
Millions
MULTI-HAZARD
ADAPTATION
Historic
2015-2040
2041-2070
2071-2100


Economic damages (€) on properties (Multi-hazard vs. adaptation)
Barberà del Vallès
Begues
Castellbisbal
Cerdanyola del Vallès
Cervelló
Corbera de Llobregat
Cornellà de Llobregat
Esplugues de Llobregat
Gavà
L'Hospitalet de Llobregat
Molins de Rei
Montgat
Pallejà
La Palma de Cervelló
El Papiol
El Prat de Llobregat
Ripollet
Sant Adrià de Besòs
Sant Climent de Llobregat
Sant Feliu de Llobregat
Sant Joan Despí
Sant Just Desvern
Sant Vicenç dels Horts
Santa Coloma de Cervelló
Santa Coloma de Gramenet
Tiana
Torrelles de Llobregat
0
1
2
3
4
5
6
7
8
9
10
Millions
MULTI-HAZARD
ADAPTATION
Historic
2015-2040
2041-2070
2071-2100

5.3.4 Adaptation scenario risk for risk receptor Waste

Adaptation scenario risk assessment of PLUVIAL FLOODS and STORM SURGE on WASTE SECTOR

Adaptation scenario risk assessment methodology

The methodology used for this multi-hazard risk assessment is the same as presented in Section 5.1.4. The difference between the scenarios concerns the hazard assessment dimension as explained in Sections 4.2.1 (AMB CS hazard assessment model) and 4.3.1 (AMB CS risk assessment scenarios). Additionally, the hazard model for this assessment considers the adaptation measures in section 4.4.1.

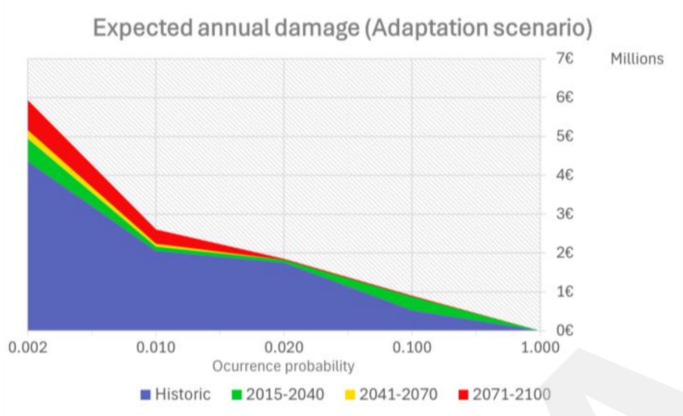
Impact assessment results

The findings from this impact evaluation demonstrate the vulnerability of the waste sector event with applied adaptation measures, particularly during severe precipitation events (T50 and above). For the adaptation scenario, modelled scenarios will impact local recycling facilities, a composting plant, a triage plant and ecoparcs.

As illustrated in the table below, local recycling centers account for the majority of financial losses resulting from flood events. Ecoparcs experience impacts only during T50 events and above, and the affected composting plant only for T100 and T500 events. Local recycling centers can suffer damages exceeding 1M € for a T50 event and can reach up to 5M € in the worst-case scenario (T500 event in the furthest future projection). Ecoparcs could face losses approaching 50.000 € for a T50 in the near future but can get to a monetary impact of 400.000 € on extreme events.

	Economic damage on waste sector for the return periods considered (and percentage of increase with respect to historic event)					
Projection Period	**T1**	**T10**	**T50**	**T100**	**T500**	**Expected annual damage**
Local recycling centre (Deixalleria)						
Historic	0 €	529,007 €	1,751,111 €	2,056,599 €	4,085,352 €	372,864 €
2015-2040	0 €	873,380 €	1,827,705 €	2,161,342 €	4,674,916 €	548,355 € (+47.1%)
2041-2070	0 €	873,474 €	1,827,705 €	2,239,844 €	4,893,042 €	549,980 € (+47.5%)
2070-2100	0 €	906,912 €	1,852,255 €	2,472,993 €	5,624,972 €	572,495 € (+53.5%)
Ecoparcs						
Historic	0 €	0 €	0 €	0 €	48,827 €	195 €
2015-2040	0 €	0 €	0 €	2,081 €	48,827 €	214 € (+9.6%)
2041-2070	0 €	0 €	0 €	2,081 €	48,827 €	214 € (+9.6%)
2070-2100	0 €	0 €	0 €	48,827 €	48,827 €	635 € (+225%)
Composting Plant (Planta de Compostatge)						
Historic	0 €	0 €	0 €	0 €	216,077 €	864 €
2015-2040	0 €	0 €	0 €	0 €	216,077 €	864 € (+0,0%)

2041-2070	0 €	0 €	0 €	0 €	216,077 €	864 € (+0,0%)
2070-2100	0 €	0 €	0 €	86,967 €	260,580 €	1,825 € (+111%)
Total waste sector						
Historic	0 €	529,007 €	1,751,111 €	2,056,599 €	4,350,256 €	373,924 €
2015-2040	0 €	873,380 €	1,827,705 €	2,163,424 €	4,939,820 €	549,433 € (+46.9%)
2041-2070	0 €	873,474 €	1,827,705 €	2,241,926 €	5,157,945 €	551,058 € (+47.4%)
2070-2100	0 €	906,912 €	1,852,255 €	2,608,787 €	5,934,378 €	574,955 € (+53.8%)

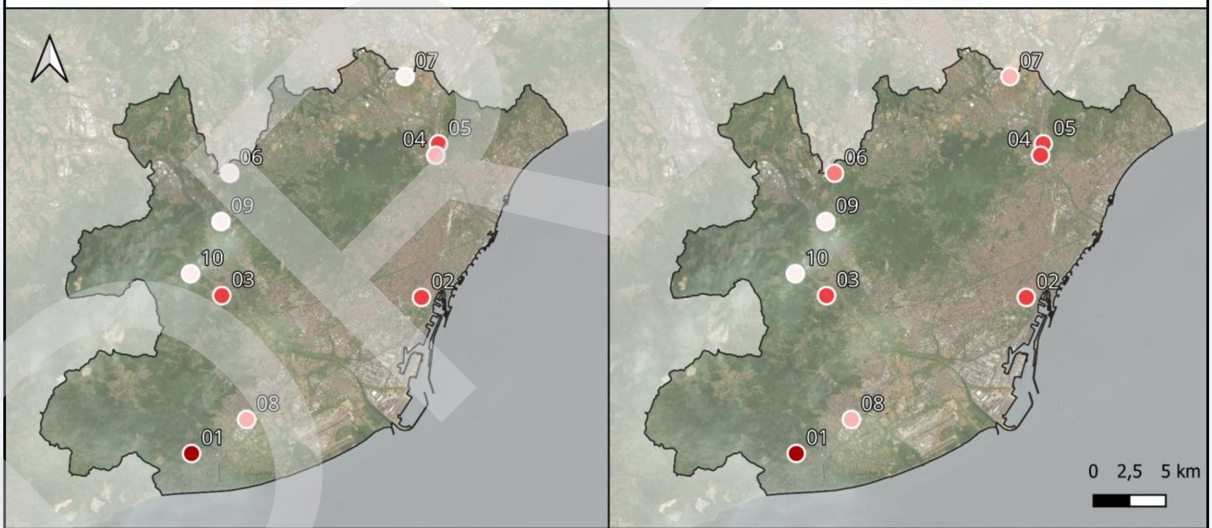


The projected annual damage to local recycling facilities shows an increase of over 26% when compared to historical records for the 2071-2100 period, with corresponding increases in total waste sector damages.

The illustration below identifies the particular facilities impacted by a T100 event, contrasting historical data with the 2071-2100 period. As depicted in the figure and previously noted, local recycling centers bear the greatest impact from these flooding events, with the Deixalleria de Castelldefels being especially vulnerable

Total damage (€) for each waste insfrastructure - Adaptation scenario

T100 Historic	T100 2071-2100



Total damage (€)
- 0 - 10.000
- 10.000 - 50.000
- 50.000 - 100.000
- 100.000 - 500.000
- 500.000 - 1.5 M

id	Name	T100 Historic - €	T100 P3 - €
01	Deixalleria de Castelldefels	1215601	1472063
02	Punt Verd barri Folch i Torres	440161	440161
03	Deixalleria de Sant Vicenç dels Horts	200277	275734
04	Punt Verd zona Vallbona	41762	120277
05	Deixalleria de Santa Coloma de Gramenet	107955	114995
06	Planta de compostatge de Sant Cugat	0	86967
07	Ecoparc 2 Montcada i Reixac	0	48827
08	Deixalleria de Viladecans	33627	33627
09	Deixalleria del Papiol	9990	9249
10	Deixalleria de Cervelló	6452	6888

Comparison between the multi-hazard and the adaptation scenarios

Return period	Modelling scenario	Climate change projection period			
		Historic	2015-2040	2041-2017	2071-2100
T1	Multi-hazard scenario	0	0	0	0
	Adaptation scenario	0	0	0	0
	Difference	-	-	-	-
T10	Multi-hazard scenario	0.62 M€	0.96 M€	1.03 M€	1.05 M€
	Adaptation scenario	0.53 M€	0.87 M€	0.87 M€	0.91 M€
	Difference	– 15%	– 9%	– 16%	– 13%
T50	Multi-hazard scenario	1.77 M€	1.83 M€	1.83 M€	1.91 M€
	Adaptation scenario	1.75 M€	1.83 M€	1.83 M€	1.85 M€
	Difference	– 1%	-	-	– 3%
T100	Multi-hazard scenario	2.12 M€	2.24 M€	2.24 M€	2.64 M€
	Adaptation scenario	2.06 M€	2.16 M€	2.24 M€	2.61 M€
	Difference	– 3%	– 4%	-	– 1%
T500	Multi-hazard scenario	4.39 M€	5.15 M€	5.37 M€	5.96 M€
	Adaptation scenario	4.35 M€	4.94 M€	5.16 M€	5.93 M€
	Difference	– 1%	– 4%	– 4%	– 1%
EAD	Multi-hazard scenario	0.43 M€	0.59 M€	0.63 M€	0.65 M€
	Adaptation scenario	0.37 M€	0.55 M€	0.55 M€	0.57 M€
	Difference	– 14%	– 7%	– 13%	– 12%

5.3.5 Adaptation scenario risk for risk receptor Electricity

Adaptation scenario risk on ELECTRICITY

Risk assessment methodology

The risk assessment for this section follows the same methodology as outlined in section 5.1.9. In this instance, it utilizes the adaptation scenarios detailed in Section 5.3. Additionally, the hazard model for this assessment considers the adaptation measures in section 4.4.1.

Impact assessment results

Similarly, as shown in section 5.1.9, several results will be presented and, on this occasion, compared with the single-hazard scenario.

The following table shows the repair time for each electrical installation and the comparison with. The important highlights regarding the reparation time are the following:

- Long-term Severity Escalation: Under the SSP5-8.5 high-emission scenario, repair times consistently increase over time. For a T500 return period, downtime increases from 14.53 days (Historic) to 15.8 days by the 2071–2100 horizon.
- The Multi-Hazard Penalty: The data highlights a significant "penalty" when compound hazards are considered. During the 2071–2100 period, the T1 event shows a 20.37% increase in repair time relative to single-hazard models, whereas the T500 event shows a 16.18% increase.
- Early Century Stabilization: In the 2015–2040 and 2041–2070 periods, intermediate return periods (T50, T100) show comparison ratios slightly below 100%. This suggests that for moderate events, the dominant hazard dictates the timeline, whereas extreme late-century scenarios trigger complex compound failures.

Return period	Maximum Repair Time (days) Single hazard difference (%)			
	Climate change projection period			
	Historic	2015-2040	2041-2070	2071-2100
T1	0.34 (0.21)	2.46 (0.00)	2.47 (0.00)	1.54 (20.37)
T10	5.35 (-1.3)	5.73 (-1.85)	5.92 (10.55)	6.25 (-1.94)
T50	9.04 (-1.53)	10.4 (-1.27)	10.52 (-1.24)	11.34 (-0.95)
T100	11.23 (-1.08)	12.13 (-0.74)	12.21 (-0.73)	12.81 (-0.71)
T500	14.53 (-0.67)	15.09 (-0.62)	14.94 (-2.29)	15.8 (16.18)

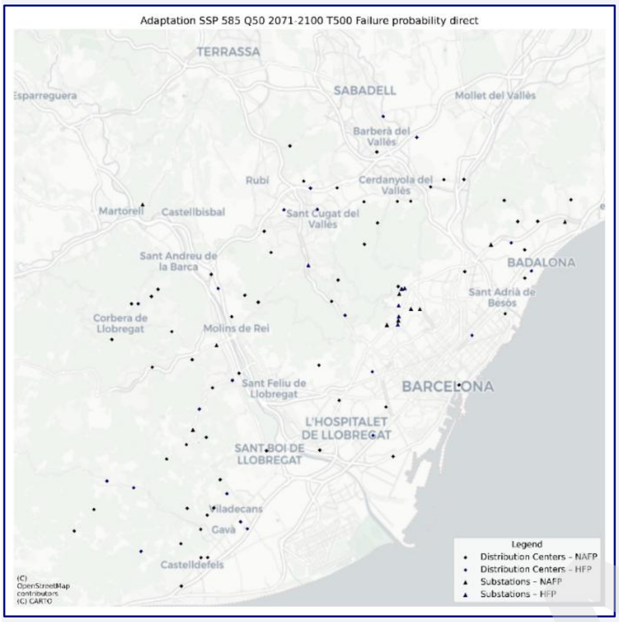
The damage costs for the multi-hazard flood are presented in the table below. The important aspects are the following:

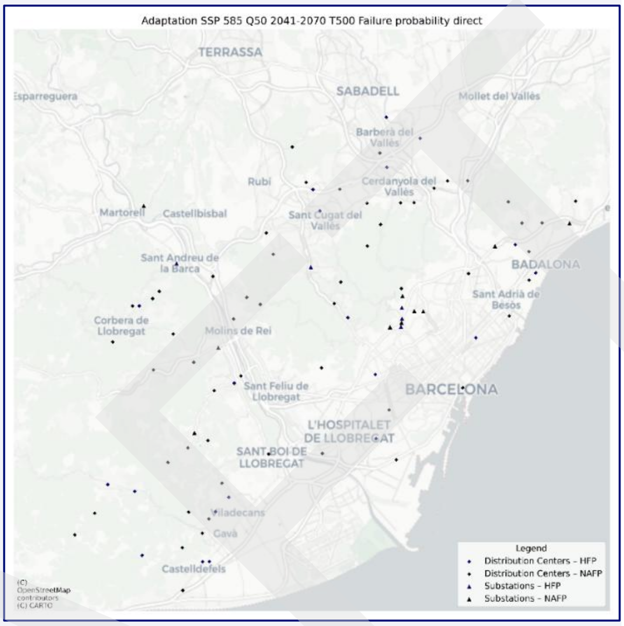
- Exponential Growth of High-Frequency Risk (T1): T1 events—historically representing zero or negligible damage—are projected to cause 0.17 M€ in direct damage by 2100. This represents a 103.45% increase over single-hazard expectations, highlighting that frequent, low-magnitude flooding will transition into a primary financial driver.
- Catastrophic Event Costs (T500): Damage for T500 events is projected to reach 11.4 M€ by the 2071–2100 horizon, which is 13.88% higher than what single-hazard models alone would predict.
- Intermediate Period Shifts: For T100 events, the damage cost increases from 6.32 M€ (Historic) to 7.9 M€ (2071–2100). The multi-hazard interaction adds a 5.12% premium to the cost of these events by the end of the century.

Return period	Damage Cost (M€) Single hazard difference (%)			
	Climate change projection period			
	Historic	2015-2040	2041-2070	2071-2100
T1	0 (-40)	0.13 (43.45)	0.14 (49.53)	0.17 (103.45)
T10	2.62 (-2.71)	2.86 (0.37)	2.99 (26.44)	3.14 (3.72)
T50	4.5 (-0.27)	5.24 (-1.83)	5.41 (-1.63)	6 (-0.78)
T100	6.32 (0.25)	6.99 (4.36)	7.16 (4.49)	7.9 (5.12)
T500	10.01 (2.17)	10.52 (4.53)	10.03 (-4.28)	11.4 (13.88)

These results confirm that the Barcelona Metropolitan Area's electrical grid is facing an accelerating resilience gap driven by the synergy of multi-hazard flood events. The 2071–2100 climate horizon (SSP5-8.5) represents a critical tipping point where compound flood effects—the simultaneous occurrence of sea-level rise and extreme pluvial discharge—disproportionately increase both the duration of recovery and the direct damage costs.
The emergence of a 20.37% time penalty and a 103.45% cost increase for high-frequency events (T1) indicates that the grid's current design is ill-equipped for the "new normal" of late-century flooding. These findings prove that relying on traditional single-hazard risk assessments will lead to a systemic underestimation of future vulnerabilities. To maintain energy security, infrastructure adaptation strategies must transition from reactive repair protocols to proactive hardening that specifically accounts for the non-linear impacts of compound flooding on the network's most critical nodes.

The following images illustrate the difference between T500 for 2041-2070 and T500 for 2071-2100. In this case, there is a slight increase in the affected installation, but the affected installation zones change due to the new flood map.





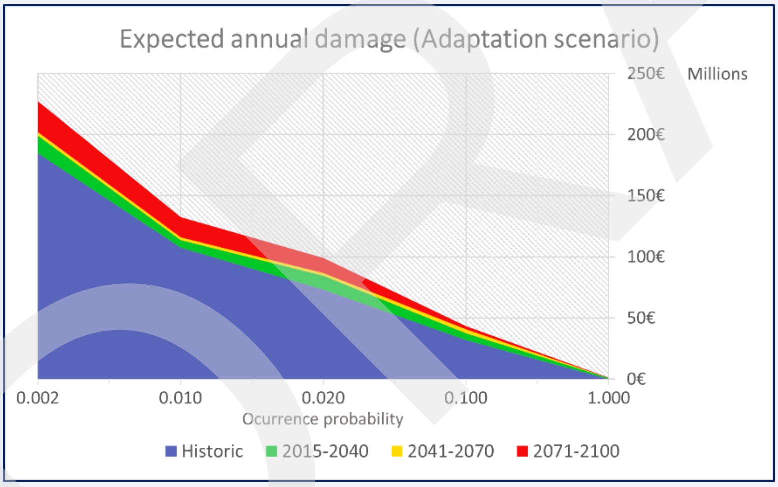
In a summary for this section, adaptation measures can reduce the effects on the electrical system, but these measures have to be taken into account from an electrical perspective, as the electrical system is not spread homogeneously, and there are critical zones that should be protected or taken into account to adapt to future events.

5.3.6 Indirect economic damages of adaptation scenario

Adaptation scenario risk assessment of INDIRECT ECONOMIC DAMAGE of PLUVIAL FLOODS
Risk assessment methodology
The risk assessment for this section follows the same methodology as outlined in section 5.1.10. In this instance, it utilizes the adaptation scenarios detailed in Section 5.3. Additionally, the hazard model for this assessment considers the adaptation measures in section 4.4.1.
Impact assessment results
The results of the adaptation scenario show that, while indirect economic damages continue to increase over time and with flood severity, the implementation of adaptation measures leads to a moderation of indirect losses compared to the multi-hazard baseline. This indicates that adaptation actions not only reduce direct flood damages, but also limit the propagation of economic disruptions across the metropolitan system.

Projection Period	Indirect Economic damage of pluvial floods (and percentage of increase with respect to previous event)					
	T1	T10	T50	T100	T500	Expected annual damage
Historic	10.318,94	31.830.542,89	73.224.316,99	107.364.667,59	184.628.420,55	20.601.499,49
2015-2040	763.276,12	37.534.769,18 (+17.92%)	84.478.289,39 (+15,37%)	113.766.267,10 (+5,96%)	198.965.884,44 (+7,77%)	24.356.794,12 (+18,23%)
2041-2070	796.294,62	40.800.419,65 (+8.70%)	86.805.323,97 (+2,75%)	115.853.520,47 (+1.83%)	201.729.011,17 (+1,39%)	26.106.375,51 (+7.18%)
2071-2100	1.229.698,90	43.217.770,67 (+5,92%)	99.011.094,12 (+14,06%)	132.455.850,92 (+14,33%)	227.223.622,24 (+12,64%)	28.286.568,52 (+8.35%)

For the Historical period, total indirect damages amount to approximately €31.8 million for T10 events and €184.6 million for T500 events, with an Expected Annual Damage (EAD) of €20.6 million. In the 2015–2040 horizon, indirect damages increase to around €37.5 million (T10) and €199.0 million (T500), while the EAD rises to €24.4 million, representing an increase of approximately 15–18% depending on the return period. For 2041–2070, indirect damages reach about €40.8 million (T10) and €201.7 million (T500), with an EAD of €26.1 million. The rate of increase relative to the previous period becomes more moderate, suggesting a stabilizing effect of adaptation measures over the medium term. The 2071–2100 horizon represents the most adverse future conditions under the adaptation scenario. In this period, indirect damages rise to approximately €43.2 million for T10 events, €132.5 million for T100 events, and €227.2 million for T500 events, while the EAD reaches €28.3 million. Although damages continue to grow towards the end of the century, their overall magnitude remains contained compared to the multi-hazard configuration without adaptation.



Overall, the increase in EAD from €20.6 million (Historical) to €28.3 million (2071–2100) reflects a progressive intensification of long-term indirect flood risk, but at a moderated pace due to the implementation of adaptation measures.

As in the previous assessments, indirect impacts are unevenly distributed across economic activities, although their overall magnitude is reduced compared to the multi-hazard scenario.

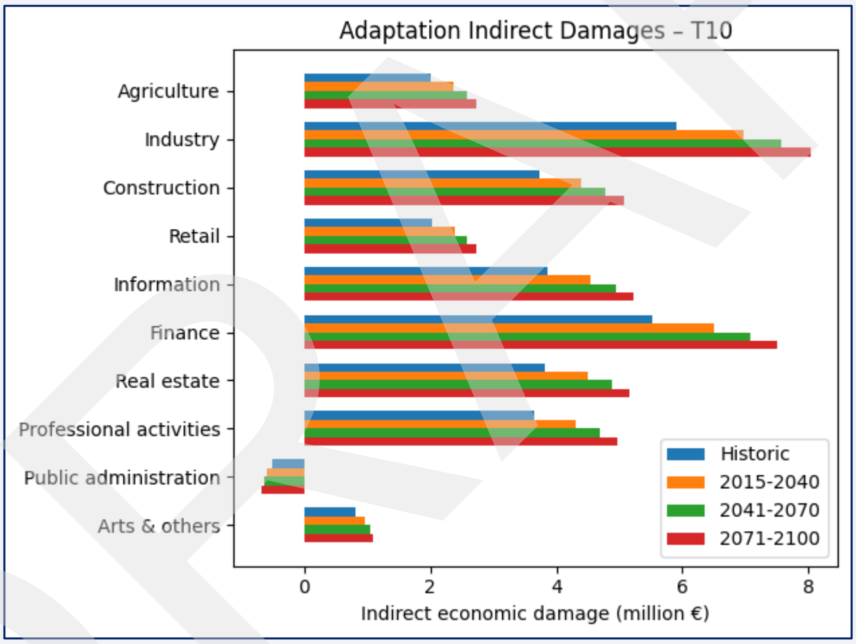
Across all time horizons and return periods, industry and financial activities represent the largest share of indirect damages, jointly accounting for roughly 35–40% of total losses. Under extreme events (T500) in the 2071–2100 period, indirect damages reach approximately €42.2 million in industry and €39.4 million in finance, confirming their strong sensitivity to cascading disruptions.

A second group of significantly affected sectors includes construction, real estate, professional activities, and information and communication services, each contributing around 10–12% of total indirect damages. For T500 events in the late-century period, losses in these sectors range between €26 million and €29 million, indicating that adaptation reduces but does not eliminate systemic economic impacts.

Agriculture and retail exhibit lower absolute indirect damages, reflecting their smaller economic weight in the AMB. Nevertheless, under extreme events in 2071–2100, losses in these sectors exceed €14 million, highlighting their continued vulnerability to compound disruptions.

The public administration sector shows a negative contribution across all periods and return levels, consistent with the econometric specification used to estimate sectoral sensitivities. This should be interpreted as a comparatively lower exposure to business interruption effects rather than as an economic gain.

Finally, arts and other services account for a smaller but steadily increasing share of indirect damages, reaching nearly €5.8 million for T500 events in the 2071–2100 period.



Comparison between the single-hazard and the multi-hazard scenarios

A comparison between the Multi-Hazard (MH) and Adaptation scenarios shows that adaptation measures generate a systematic reduction in long-term indirect flood risk, particularly when assessed through Expected Annual Damage (EAD).

In the Historical baseline, EAD decreases from €24.1 million (MH) to €20.6 million (Adaptation), representing a reduction of approximately 15%. For the 2015–2040 period, EAD declines from €28.0 million under MH to €24.4 million with Adaptation, corresponding to a reduction of roughly 13%. In the 2041–2070 horizon, EAD decreases from €29.5 million (MH) to €26.1 million (Adaptation),

representing a reduction of about 11–12%. By the end of the century (2071–2100), EAD is reduced from €32.9 million in the MH scenario to €28.3 million under Adaptation, equivalent to a reduction of approximately 14%.
These results demonstrate that adaptation measures consistently lower the long-term average annual indirect economic risk by around 11–15% across all time horizons. While indirect damages still increase over time due to growing hazard intensity and economic exposure, adaptation significantly dampens the propagation of economic shocks through the metropolitan system.

5.3.7 Cascading effects related to the adaptation scenario

Adaptation scenario of cascading effects on ELECTRICITY

Cascading risk assessment methodology

The methodology to assess the cascading effect on adaptation scenarios is the same as exposed on section 5.1.10.

Cascading effect results

Using the results of the risk assessment on the electricity of the AMB in the same scenario. The following table shows information about the consumers and electrical assets affected by the cascading effects, followed by the highlights of each table:

Return period	Affected consumers Single hazard difference (%)			
	Climate change projection period			
	Historic	2015-2040	2041-2070	2071-2100
T1	0 (0)	0 (0)	0 (0)	0 (0)
T10	1175 (0.17)	1175 (0.17)	1175 (20.27)	1181 (-20.2)
T50	5227 (-11.09)	6496 (0.12)	6496 (-5.25)	7256 (0.11)
T100	7369 (0.38)	7456 (0.38)	7456 (0.38)	8231 (8.16)
T500	14821 (0.32)	14945 (0.34)	10808 (-27.45)	17022 (42.11)

- Extreme Scalability in Late-Century Events (T500): The most significant impact occurs in the 2071–2100 horizon for T500 events, where affected consumers reach 17,022. This represents a 42.11% increase compared to single-hazard projections, highlighting how compound flooding disproportionately expands the footprint of service disruption.

- Intermediate Return Period Growth: For T100 events, the number of affected consumers rises from 7,369 (Historic) to 8,231 (2071–2100), with an 8.16% multi-hazard penalty at the end of the century.
- T10 Paradox: Interestingly, while the absolute number of affected consumers for T10 increases slightly (from 1,175 to 1,181), the single hazard difference for the 2071–2100 period is -20.2%, suggesting that at this specific frequency, the single-hazard separation could over-allocate consumers compared to the integrated multi-hazard intersection.

Return period	Affected installations only cascading			
	Climate change projection period			
	Historic	2015-2040	2041-2070	2071-2100
T1	0	0	0	0
T10	0	0	0	0
T50	1	1	1	0
T100	0	0	0	2
T500	19	17	1	17

- Systemic Increase in Asset Exposure: The total number of affected installations for T500 events increases from 44 (Historic) to 51 (2071–2100). The multi-hazard interaction results in a 10.87% increase in exposure relative to single-hazard assessments in the final period.
- Critical Thresholds for T100: For T100 events, the number of damaged installations grows from 30 to 34 by 2100, with a 13.33% difference attributable to multi-hazard synergy.
- Low-Frequency Resilience: T1 events show zero affected installations across all climate horizons, indicating that the network's physical hardening or elevation is currently sufficient to withstand very high-frequency flood events without structural failure.

Return period	Affected installations total Single hazard difference (%)			
	Climate change projection period			
	Historic	2015-2040	2041-2070	2071-2100
T1	0 (0)	0 (0)	0 (0)	0 (0)
T10	10 (11.11)	10 (11.11)	10 (25)	11 (10)
T50	16 (-15.79)	23 (9.52)	23 (4.55)	27 (8)
T100	30	32	32	34

	(11.11)	(10.34)	(10.34)	(13.33)
T500	44 (2.33)	47 (6.82)	45 (0)	51 (10.87)

- Dominance of T500 Cascades: Cascading failures are almost exclusively linked to extreme T500 events. In the 2071–2100 period, 17 installations are projected to fail due to cascading effects.
- Non-Linear Vulnerability: There is a notable "dip" in the 2041–2070 period where only 1 installation fails via cascade for T500, compared to 19 in the Historic period. This may reflect a shift in flood polygons that bypasses critical "hub" nodes during that specific timeframe.
- Emergent Cascades in T100: By the 2071–2100 period, the model identifies 2 installations failing via cascade for T100 events—a phenomenon not seen in earlier climate horizons, signaling that the grid's operational margin of safety is eroding.

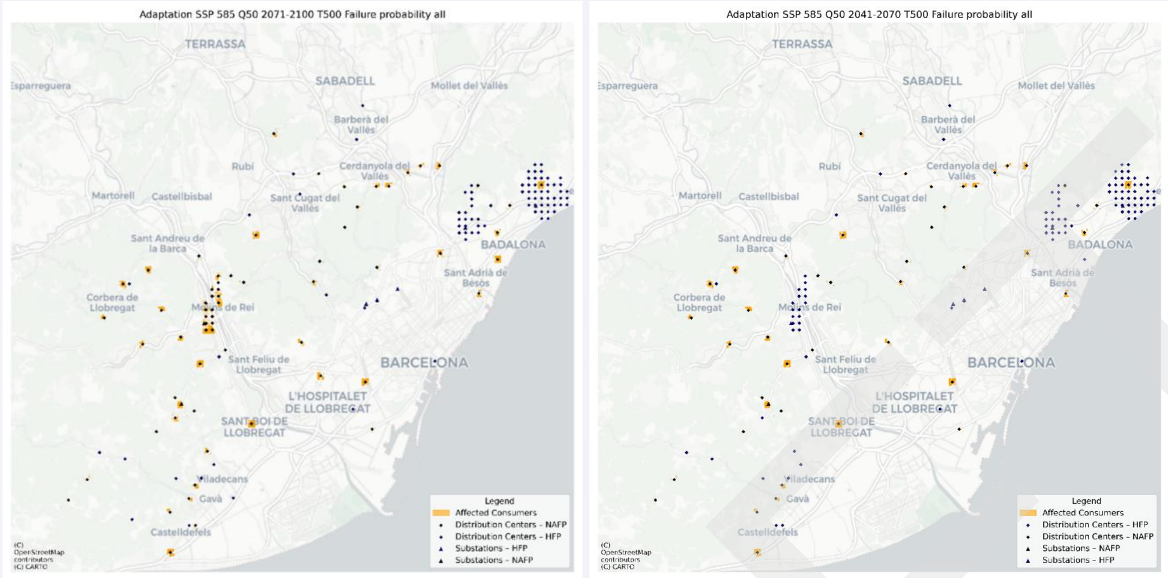
Return period	**Energy None Supplied Cost (k€)** Single hazard difference (%)			
	Climate change projection period			
	Historic	**2015-2040**	**2041-2070**	**2071-2100**
T1	0.01 (-56.04)	9.50 (15.45)	10.47 (17.19)	10.78 (24.53)
T10	97.74 (-6.87)	107.11 (-1.64)	110.64 (12.4)	115.33 (2.38)
T50	144.98 (-5.51)	155.43 (-6.16)	159.14 (-7.47)	168.24 (-6.84)
T100	176.78 (-7.67)	191.78 (5.48)	194.79 (5.87)	208.65 (6.4)
T500	240.15 (5.71)	250.52 (8.64)	231.95 (-3.3)	265.04 (15.9)

- Acceleration of High-Frequency Impact (T1): While historically negligible, the ENS cost for T1 events surges to 10.78 k€ by 2100. The "Single hazard difference" grows significantly, reaching 24.53%, indicating that high-frequency events will cause disproportionately more economic disruption under multi-hazard conditions.
- Peak Economic Risk (T500): The cost for catastrophic T500 events rises from 240.15 k€ (Historic) to 265.04 k€ (2071–2100). In the final period, the multi-hazard synergy adds a 15.9% penalty compared to single-hazard models.
- Consistency in Intermediate Risks: For T50 events, the ENS cost remains consistently higher in the multi-hazard model than in single-hazard models, though the difference remains negative (approx. -6.84% in 2100), suggesting that coastal or pluvial models individually might overestimate ENS for moderate return periods.

Return period	Auxiliar Generation Cost (M€) Single hazard difference (%)			
	Climate change projection period			
	Historic	2015-2040	2041-2070	2071-2100
T1	0 (0)	0.15 (27.12)	0.17 (30.5)	0.17 (47.59)
T10	1.93 (-9.78)	2.11 (-5.28)	2.18 (9.59)	2.3 (-2.79)
T50	3.04 (-11.68)	3.37 (-15.62)	3.48 (-19.19)	3.77 (-17.45)
T100	3.91 (-15.24)	4.44 (-7.48)	4.51 (-7.62)	4.88 (-6.32)
T500	5.98 (-1.95)	6.26 (0)	5.85 (-9.87)	6.72 (8.72)

- Surge in Mitigation Costs for T1: Similar to ENS, the cost of auxiliary generation for T1 events jumps from 0 to 0.17 M€ by 2100. The multi-hazard interaction adds a 47.59% premium to these costs, signaling a massive increase in the logistics of maintaining high-frequency grid resilience.
- Stabilization of Large-Scale Mitigation: For T100 events, the AGC reaches 4.88 M€ by 2100. Interestingly, the multi-hazard model shows lower costs than the single-hazard baseline (-6.32%), which may indicate that the spatial intersection of hazards reduces the "redundant" deployment of auxiliary units compared to treating coastal and pluvial risks separately.
- Correlation with Asset Failure: The AGC strictly follows the physical failure of installations, peaking at nearly 5 M€ for return periods where primary substations are compromised.

The following images illustrate the difference between T500 for 2041-2070 and T500 for 2071-2100. In this case, there is a slight increase in the affected installation, but the affected consumers are different.



Similar to the direct risk assessment for adaptation scenario, there are some cases where the taken measures reduce the effects, there are other scenarios where the measures can even make it worse. For these reasons, the adaptation measures should account for all critical systems.

5.3.8 Benefits and Co-Benefits of the Adaptation Scenario of the AMB CS

The adaptation scenario developed for the Barcelona Metropolitan Area (AMB) combines three complementary measures—porous pavements, green roofs, and bioretention areas—implemented in a distributed manner across the region. Although each measure operates at different spatial scales and targets distinct components of the urban hydrological system, their combined implementation forms a coherent strategy aimed at reducing flood hazard while delivering multiple co-benefits across environmental, social, and urban resilience dimensions. Beyond the risk and economic damage reduction capacity of the proposed adaptation strategy, this section presents its main associated co-benefits. This perspective is relevant to complement a cost benefit analyses with a well-informed multi-criteria analysis of adaptation strategies at the regional level

From a hydrological perspective, the three measures act in synergy to reduce effective imperviousness, increase interception and temporary storage, and delay runoff generation. Porous pavements eliminate runoff generation over a portion of the street network, particularly in urban areas where flood damages are concentrated. Green roofs increase initial losses and surface roughness on buildings, reducing runoff volumes and delaying peak flows. Bioretention areas further reduce runoff by promoting infiltration, evapotranspiration, and controlled exfiltration, while also improving stormwater quality. At the metropolitan scale, these distributed effects contribute to flatter hydrographs, reduced peak discharges, and lower pressure on sewer and drainage systems during extreme rainfall events.

Beyond flood risk reduction, the proposed measures generate significant co-benefits for citizens. In particular, the scenario contributes to improved thermal comfort and heatwave resilience. Green roofs reduce roof surface temperatures and indoor heat stress in public buildings, while bioretention areas provide localized cooling through vegetation and evapotranspiration at street level. The combined increase in vegetated and permeable surfaces contributes to mitigating the urban heat island effect, which is especially relevant in dense neighborhoods of the AMB. These effects are associated with reduced heat-related health impacts and improved outdoor comfort during extreme temperature events.

Public health and well-being are further enhanced through improvements in air quality and urban amenity. Vegetated systems associated with green roofs and bioretention areas contribute to the capture of airborne pollutants and particulate matter. Bioretention areas, in particular, transform conventional drainage infrastructure into visible, multifunctional urban elements, improving the quality and usability of public space and supporting more livable streets.

The adaptation scenario also offers substantial environmental co-benefits. Bioretention areas provide effective removal of pollutants from stormwater runoff through filtration, biological uptake, and microbial processes, leading to improved water quality downstream. Together with porous pavements and green roofs, these systems support groundwater recharge where local conditions allow, contributing to improved water resource efficiency. Moreover, the increase in vegetated surfaces enhances urban biodiversity and ecological connectivity, especially in densely built environments where ground-level green space is limited.

Although the measures are primarily designed to address pluvial flooding, they also contribute indirectly to reducing vulnerability to compound and coastal flood hazards. By lowering baseline runoff volumes and reducing dependency on sewer conveyance during extreme events, the adaptation scenario increases the overall robustness of the drainage system.

In summary, the adaptation scenario based on porous pavements, green roofs, and bioretention areas provides a robust reduction of flood hazard at the metropolitan scale while simultaneously delivering multiple co-benefits. These include improved thermal comfort, enhanced public health, increased urban amenity, better water quality, and strengthened ecological functions.

6 SBG Risk assessment results

6.1 Single-hazard risk assessment

6.1.1 Risk assessment of fluvial floods on properties

Risk assessment of FLUVIAL FLOODS on PROPERTIES

Risk assessment methodology

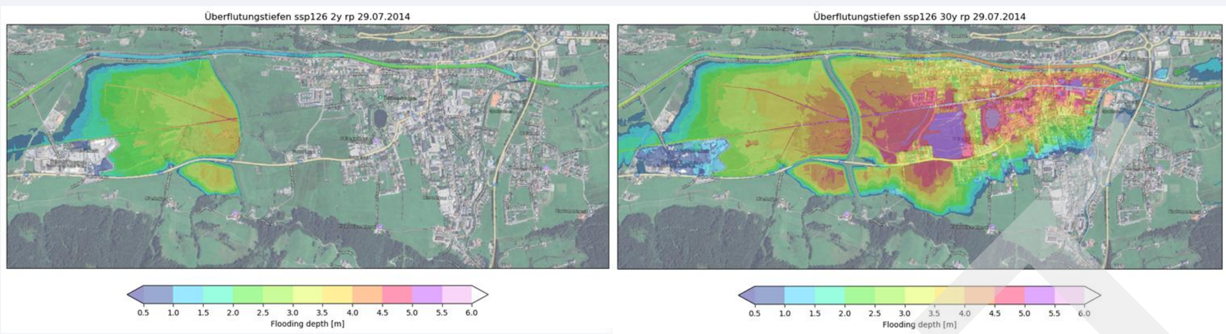
This flood assessment goal is evaluating the potential economic damages to properties within the Mittersill region. The flood risk framework combines hazard, exposure, and vulnerability components to estimate expected economic losses. The assessment was done for different scenarios and return periods, and the resulting water depths were crossed with tailored depth-damage functions to obtain the resulting economic impact.

Hazard assessment methodology

The flood depths west of Mittersill that cover the industrial area coincide well with observed past flood depths of 1 m - 1,5 m that will occur during a future 30-yr event, independent of the SSP scenario. When investigating 100-yr return periods, the industrial park will be covered by up to 2.5m in both SSPs, as the precipitation intensity doesn't differ strongly between the scenarios.
For the residential areas in Mittersill, the flood depth is overestimated since runoff possibilities within the built environment are not fully represented (e.g., canalization, connections to small streams that pass through the center). Therefore, water is accumulating unrealistically. These shortcomings could not be addressed sufficiently during the project because the data, needed to correctly represent these aspects, was not available in time. Further, the model is still under development to better represent alpine areas (with relevant input from ICARIA).

Summary of Impact Assessment Results:

Maximum flood depth	SSP1-2.6 industrial park	SSP5-8.5 industrial park	SSP1-2.6 central Mittersill	SSP5-8.5 central Mittersill
2yr RP	1 m	1 m	0 m	0 m
30 yr. RP	2 m	2 m	5 m	5 m
100 yr. RP	3 m	3 m	6 m	6 m



Flood depth for a 2yr RP event (left) and 30yr RP event under SSP1-2.6 (left); SSP5-8.5 displays the same pattern

Exposure assessment of PROPERTIES

The exposure of properties of the Mittersill region is characterized by the locations and area of buildings in the studied area. The building footprints are derived from OpenStreetMap, heights were calculated with the Digital Surface Model and Digital Terrain Model from the Federal State of Salzburg.

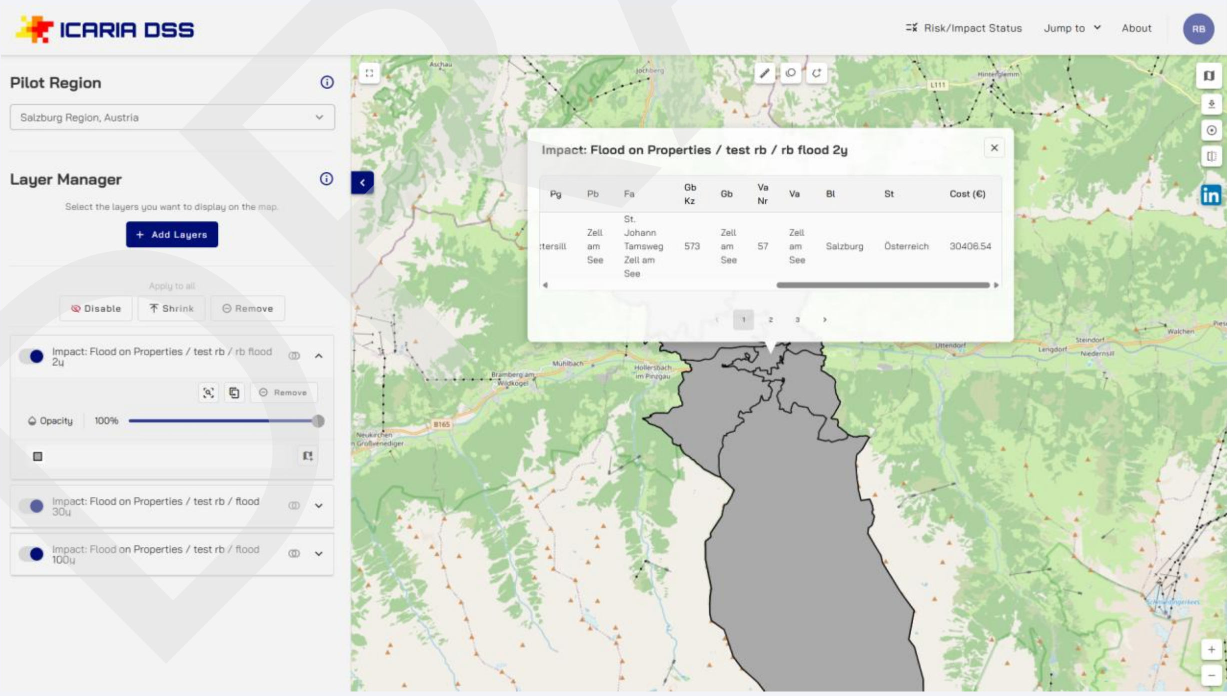
Vulnerability assessment of PROPERTIES

Vulnerability of buildings as in damage due to flood depth was assessed using the generalized vulnerability curves based on Huizinga et al. (2016) for Austria. Curves were adapted for future time horizons following the temporal transferability approach described in Martinez-Gomariz et al. (2020), according to the methodology presented in D3.1. and available within the ICARIA DSS. Curves were transferred to future time horizons by scaling their monetary values using country- and SSP-specific GDP growth factors (2020 baseline), assuming GDP as a proxy for asset value evolution. Since the majority of buildings in Mittersill are residential and no specific information on building use is available, the vulnerability curve representative of residential buildings was applied.

Impact assessment results

Based on the flood map and risk assessment described above, within the DSS the costs related to the flood damage were computed. Within the DSS the workflow “risk of flooding to properties” was implemented according to the workflow described for the AMB case study. For SBG the only difference was that the general vulnerability curves, as displayed above, were used instead of the detailed ones displayed for AMB. The results shown below represent the direct output of the DSS. For the calculation of the impact region, the census regions were used as there are no smaller administrative units available. Calculating impact on e.g., building blocks would improve the accuracy of the results. It is important to keep in mind that these range from about 30k€ for the 2yr flooding with minimal damage to about 9 M€ in the case of a 100yr event. Official numbers of the extreme flooding 2005 report of 50 M€. The difference can be explained by the fact that only residential buildings are assumed, therefore the reported damage of the hospital or infrastructure in 2005 is not reflected.

Flooding event	Impact: Flood on properties (Census region “Mittersill Markt)
2 yr. event	30.406 €
30 yr. event	1.979.055 €
100 yr. event	9.198.238 €



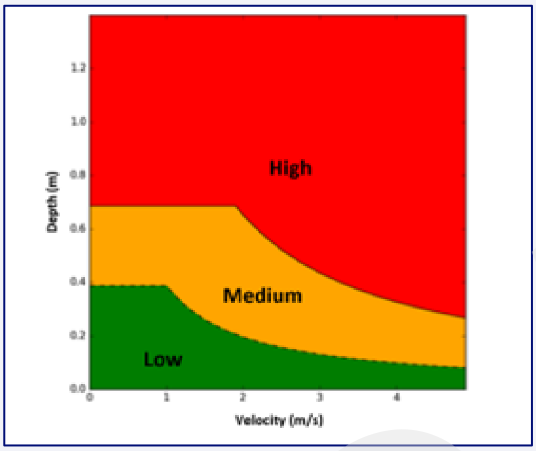
6.1.2 Risk assessment of fluvial floods on transport

Risk assessment of PLUVIAL FLOODS on TRANSPORT

Risk assessment methodology

This assessment's goal is evaluating the potential disruption of traffic in Mittersill. The risk framework combines hazard, exposure, and vulnerability components to estimate expected disruption severity.

Hazard assessment on TRANSPORT



Flood hazard intensity depends on the flood depth and velocity according to the hazard criteria developed at UPC and adopted in AMB case study (Martínez-Gomariz et al., 2016). As SFINCS only provides flood depth and Mittersill focuses on fluvial flooding, velocity was assumed to be low (<1 m/s).

Exposure assessment on TRANSPORT

For Mittersill, the roads where traffic counts are conducted were used as exposed assets.

Vulnerability assessment on TRANSPORT

Vulnerability was reflected through the indicator VFI (Vehicular Flow Intensity). This number reflects how many vehicles on average transit through a specific transport network. Roads with higher VFI are considered to have a higher vulnerability than those with lover VFI. The table below reflects vulnerability scores based on VFI extracted for Barcelona city from Evans (2019).

Vulnerability index/score	Vehicle flow intensity (VFI) (veh/day)
1 (Low)	< 5,000
2 (Medium)	5,000 ⩽ x ⩽ 10,000
3 (High)	> 10,000

Impact assessment results

		Hazard		
		Low [1]	Medium [2]	High [3]
Vulnerability	Low [1]	1	2	3
	Medium [2]	2	4	6
	High [3]	3	6	9

The combination of hazard and vulnerability in a 3x3 matrix displays the overall risk. It is high in case either the hazard and/or the vulnerability are high. For Mittersill the biggest impact is seen on the street passing the industrial area and then entering the central part of the small town. The impact is so high as both aspects are met, this street is highly travelled on (> 5.000 cars) and is flooded, depending on the specific site by 0.5 to 5m in the centre of Mittersill.

The figure above presents the impact of flooding on traffic. 0 represents no flood depth and therefore no impact, green represents low, orange medium and red high impact (due to either high flood depth and/or large number of vehicles being present)

6.1.3 Risk assessment of windstorms on properties

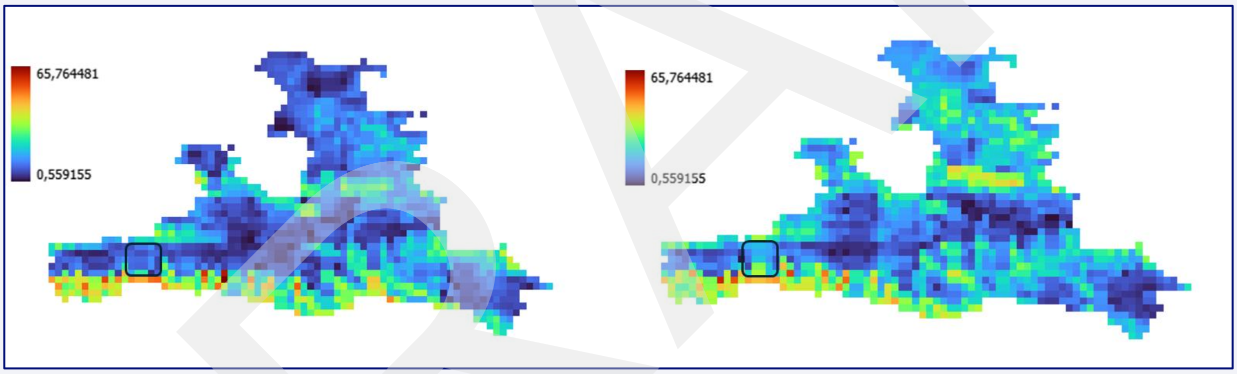
Risk assessment of WINDSTORMS on PROPERTIES

Risk assessment methodology

This assessment's goal is evaluating the potential economic damages due to windstorms to properties within the Mittersill region. The risk framework combines hazard, exposure, and vulnerability components to estimate expected economic losses. The assessment was done for different extreme wind events, resulting velocities were combined with wind-damage functions to obtain the potential economic impact.

Hazard Assessment

The simulated wind speed events had maximum intensities of about 40 m/s, thus representing extreme storms as defined by the German weather service (> 33 m/s represent the strongest storm type), yet over Mittersill the wind speed was about 20 m/s, representing a storm type that causes minimal damage to properties (source: German Weather Service, https://www.wettergefahren.de/warnungen/windwarnskala.html). This is also seen in our results using weak brick structure for the buildings.



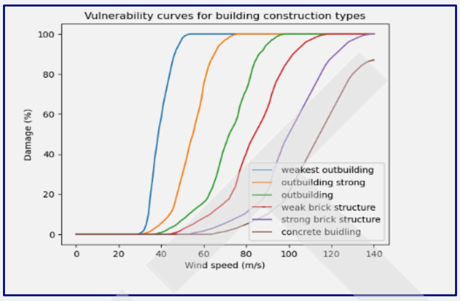
The figure above shows the event with maximum wind speeds in m/s for the federal state of Salzburg; left: SSP1-2.6, right: SSP5-8.5; Mittersill is indicated by black rectangle

Exposure assessment of PROPERTIES

The exposure of properties of the Mittersill region is characterized by the locations and area of buildings in the studied area, based on the information stated in the section "flood risk on properties".

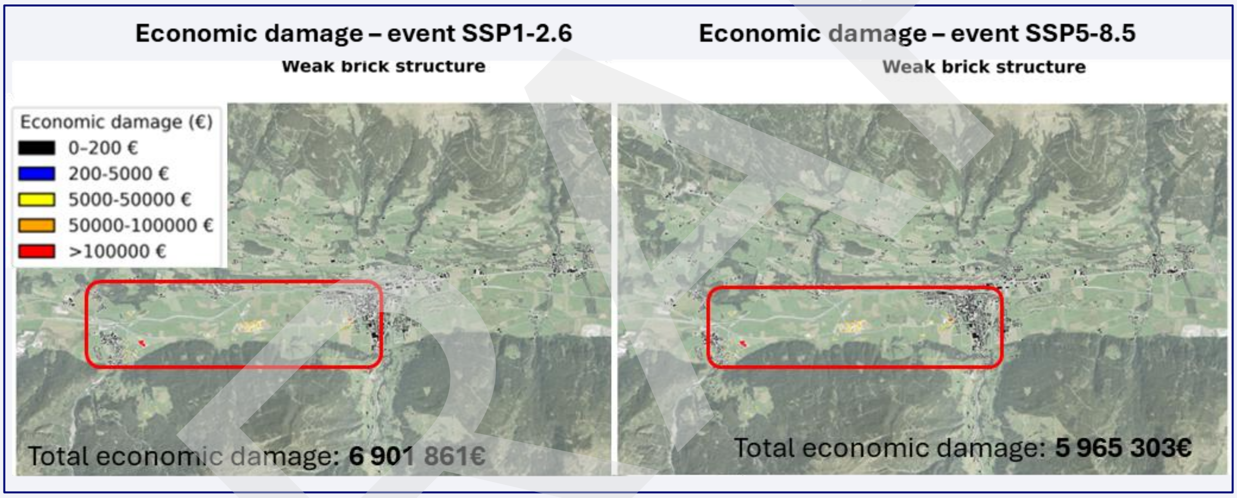
Vulnerability assessment of PROPERTIES

Vulnerability of buildings as in damage due to windstorms was assessed using the generalized vulnerability curves based on Feuerstein et al., 2011. The costs were estimated the same way as for flooding. From Koks & Haer., 2020 we know that building type of "weak brick structure" fit the best to observed damage values.



Impact assessment results

Based on the combination of wind speeds, vulnerability curves and assumed damage costs per m2, the computed damage is 0€ for most parts of central and eastern Mittersill. Yet, the western part is strongly affected, displaying singular areas with damages of more than 100.000€. Overall, a potential damage of about 6M€ is computed for the strongest wind speeds occurring within the simulations for SSP1-2.6 and SSP5-8.5.



The figure above shows the Economic Damage per building and aggregated over the whole region for most damaging events; red rectangular displays most affected area; left: SSP1-2.6; right: SSP5-8.5

An overview of the expected damage due to the most severe windstorms is given in the table below. Please note, that since there is no significant change between historic and future wind intensities, only future events are displayed.

Event	Economic impact €	Number of buildings affected
24-10-2034 SSP126	6.90e+06	714
01-03-2038 SSP585	5.97e+06	702
11-03-2090 SSP585	7.59e+05	104
18-11-2096 SSP126	9.53e+04	21
04-09-2066 SSP126	0.00e+00	0
21-03-2071 SSP585	0.00e+00	0

6.1.4 Risk assessment of windstorms on electricity network

Risk assessment of WINDSTORMS on ELECTRICITY NETWORK

Risk assessment methodology

The risk assessment integrates wind hazard intensity, infrastructure vulnerability, and spatial exposure to evaluate the potential for electricity supply disruptions during heavy wind events. Wind speed and wind direction derived from regional climate model simulations are used to characterize the hazard, focusing on maximum wind conditions representative of extreme events.

The heavy wind hazard used in this assessment is derived from spatial wind fields representing current climatic conditions across the Salzburg study area. To explore the potential consequences of more severe wind events, the baseline risk values obtained from the analysis are amplified using a scaling factor of four.

This scaling approach is applied as a stress-testing scenario to enhance spatial differentiation of risk patterns and to evaluate potential cascading and economic impacts under intensified wind conditions. The scaling does not represent a probabilistic climate projection or a specific future scenario but provides a sensitivity analysis framework to support comparative risk assessment under more extreme yet plausible hazard conditions.

Infrastructure vulnerability is represented through fragility functions assigned to overhead power lines and electrical substations. For overhead lines, failure probability is computed as a function of the incident wind component acting perpendicular to the line orientation, explicitly accounting for both wind speed and wind direction. This approach allows a more realistic representation of wind–structure interaction than using wind speed alone.

The relative angle between wind direction and line orientation is calculated as:

$$\theta_{rel} = |\theta_{azimuth} - \theta_{wind}| \; mod \; 180$$

where the line azimuth ($\theta_{azimuth}$) is derived from the geometry of each line segment:

$$\theta_{azimuth} = \text{azimuth}(\text{start\_point}(\$geometry),\text{end\_point}(\$geometry))$$

The effective incident wind speed acting on the line is then computed as:

$$V_{inc} = V_{max} \cdot sin(\theta_{rel})$$

where V_{max} is the maximum wind speed. These calculations are implemented using QGIS geometry and raster analysis tools and allow the transformation of gridded wind fields into line-specific hazard intensities. Where V_{max} is the maximum wind speed. These calculations are implemented using QGIS geometry and raster analysis tools and allow the transformation of gridded wind fields into line-specific hazard intensities.

The probability of failure of overhead power lines is subsequently derived by applying a fragility function that relates the incident wind speed V_{inc} to failure probability. The shape and parameters of the fragility curve are defined based on published vulnerability approaches for electrical distribution networks under wind hazards. For electrical substations, vulnerability is assumed to depend primarily on wind speed and is treated as isotropic, given the absence of a dominant structural orientation. Failure probability is therefore computed directly as a function of maximum wind speed using a dedicated fragility curve (Dunn et al., 2018; Ma et al., 2024; Nirandjan et al., 2024).

The resulting component-level failure probabilities provide a probabilistic representation of direct wind-induced damage to electricity infrastructure. These probabilities constitute the basis for subsequent spatial aggregation and cascading effects analysis

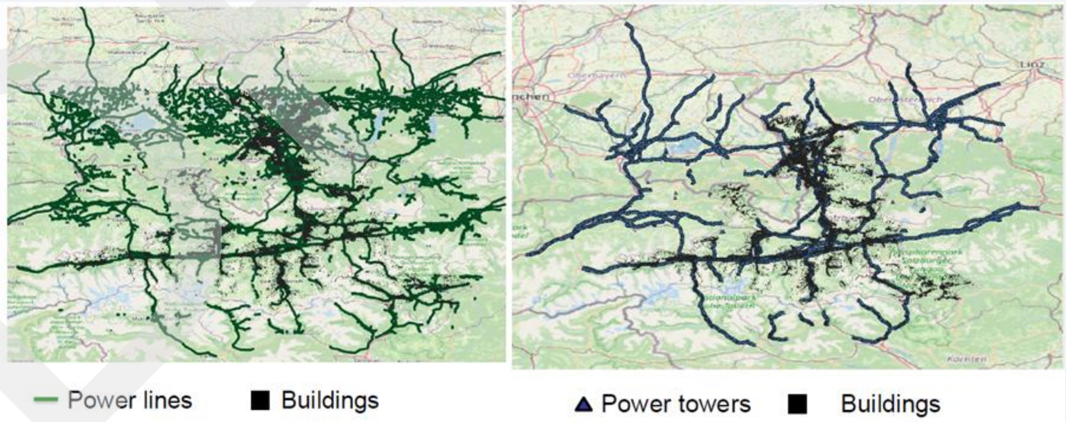
Electrical Network Topology of ELECTRICITY

Due to data access restrictions, a detailed and complete electrical network topology for Salzburg is not publicly available. Consequently, the electrical network representation used in this assessment is based on open data sources and publicly accessible information on electricity infrastructure assets.

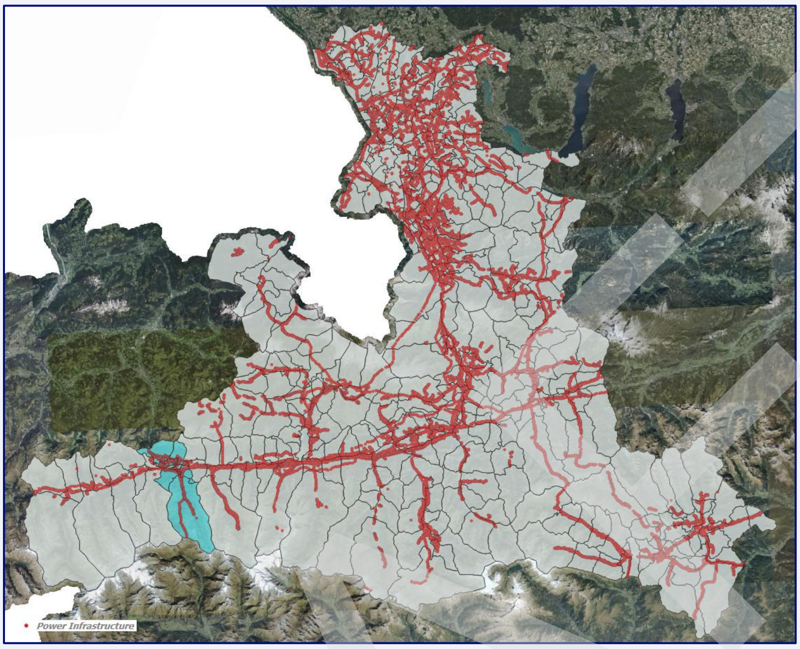
The analysis focuses primarily on overhead power lines (minor and non-underground lines), which constitute the most wind-exposed components of the electricity system. Electricity generation assets are included only for contextual representation where spatial information is available.

Using the available information and knowledge of the study area, the main electrical components and their spatial distribution are represented in a simplified manner. The network representation captures the geographic location and geometry of overhead lines, towers, and generators, while detailed information on network connectivity, voltage levels, redundancy, protection schemes, and operational configurations is not explicitly modelled.

This simplified, spatially explicit representation is designed to support hazard exposure, vulnerability assessment, and subsequent cascading effects analysis under heavy wind conditions, while remaining transparent and consistent with the level of data availability. The spatial representations of electricity infrastructure assets and buildings are based on publicly available geospatial datasets and are used exclusively for analytical and illustrative purposes.



The figure above reflects the spatial distribution of overhead power lines, power points and buildings within the study area, illustrating the exposed electricity transmission elements considered in the heavy wind risk assessment [1], [2].



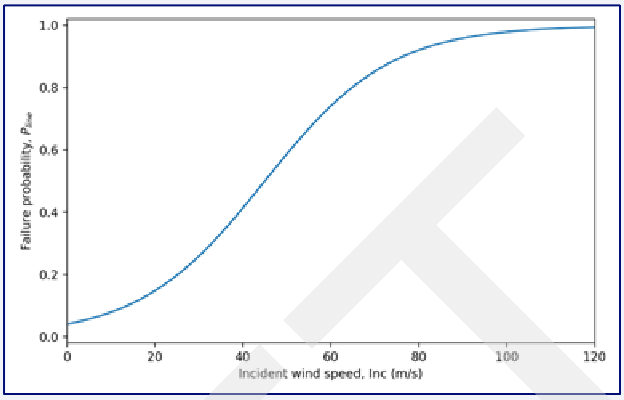
The figure above shows the Power Infrastructure derived from Open Infrastructure Map for the Federal State of Salzburg (Background map: Geoland Basemap Orthophoto)

Exposure and vulnerability assessment of ELECTRICITY

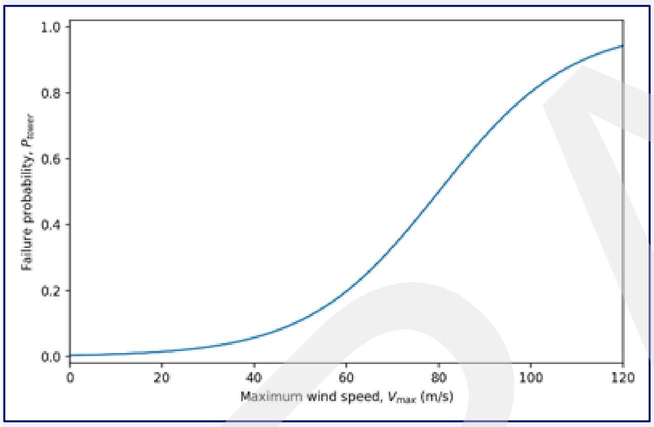
In the context of heavy wind events, the exposed electrical assets considered in this assessment are overhead power lines and electrical substations, which are directly affected by high wind speeds and wind direction. Electricity generation assets are not explicitly included within the scope of the analysis, and the assessment therefore focuses on transmission and distribution components relevant for electricity supply continuity.

Exposure is evaluated spatially by intersecting electrical assets with wind hazard surfaces representing maximum wind speed and wind direction across the study area. These hazard surfaces are derived from regional climate model outputs and allow the characterization of wind conditions acting on each electrical component.

Vulnerability is quantified using fragility functions that relate wind intensity to the probability of component failure. For overhead power lines, wind speed and wind direction are combined to compute the incident wind component acting perpendicular to the line orientation, which is then used to estimate failure probability as shown on the figure.



For electrical substations, vulnerability is assumed to depend primarily on maximum wind speed, independent of wind direction, and failure probability is derived accordingly. Vulnerability is quantified using fragility functions that relate wind intensity to the probability of component failure. For overhead power lines, wind speed and wind direction are combined to compute the incident wind component acting perpendicular to the line orientation, which is then used to estimate failure probability. For electrical substations, vulnerability is assumed to depend primarily on wind speed, independent of wind direction. This simplified approach reflects data limitations while maintaining physical consistency with wind-induced damage mechanisms.



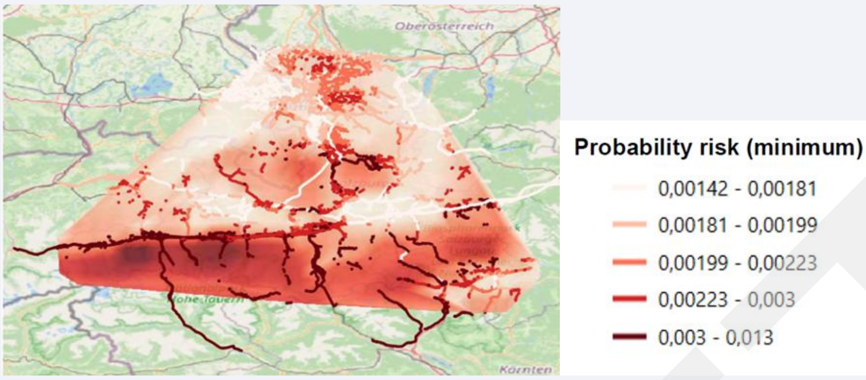
This exposure and vulnerability assessment is designed to capture relative spatial differences in potential electricity supply risk at the component level rather than to reproduce detailed operational behavior of the electrical network.

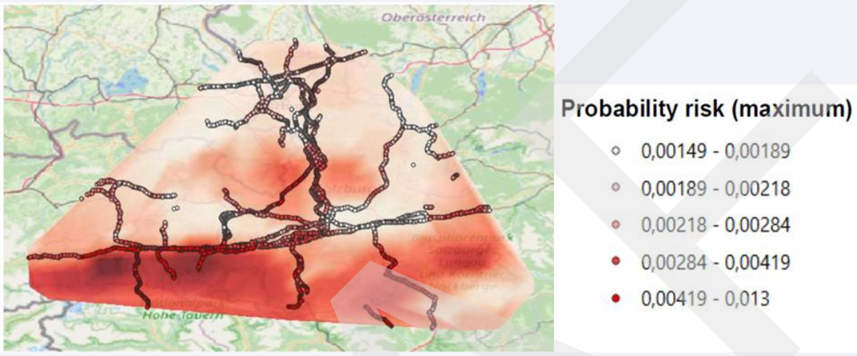
Impact assessment results

The impact assessment results highlight spatial differences in the potential consequences of electricity supply disruptions under heavy wind conditions across the Salzburg study area. Service areas characterized by higher aggregated electricity supply risk are primarily associated with zones where electrical assets intersect regions of elevated wind intensity.

When exposure is considered, the results indicate that the potential impact is strongly influenced by the spatial distribution of buildings within affected service areas. In particular, densely built zones show a higher potential impact, as localized power supply disruptions may affect a larger number of exposed assets, even under relatively low absolute failure probabilities.

The resulting maps and aggregated indicators provide a first-order representation of potential electricity supply impacts under heavy wind conditions. These results support the identification of zones where heavy wind events may lead to more pronounced indirect consequences for buildings and electricity-dependent activities.





Aggregated Impact Indicators Results

To complement the spatial patterns shown in the table below, aggregated impact indicators were derived to summarize the extent of potential electricity supply disruptions across risk levels.

Atribute	Towers	Power lines
Minimum risk	0,00148	0,0000987
Maximum risk	0,013	0,092
Average risk	~0,0038	~0,008
Probability risk > 60%	0	0

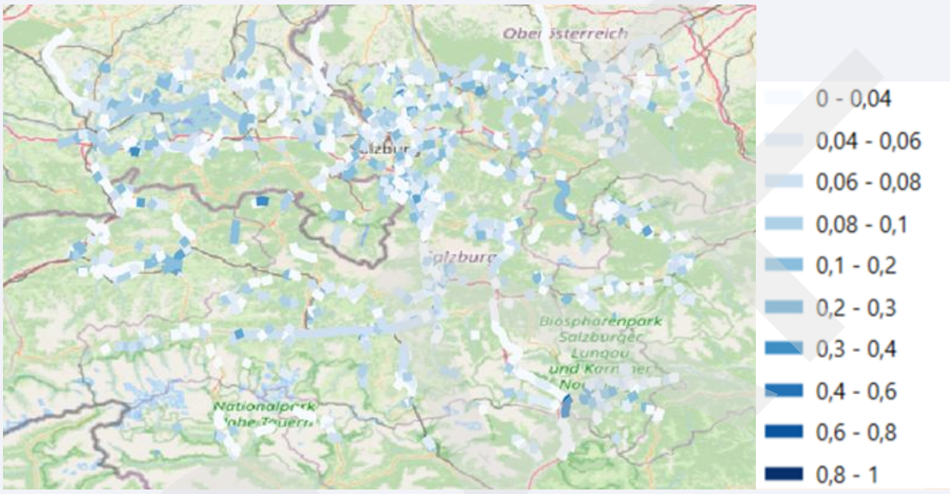
The table summarizes the aggregated impact indicators derived from the spatial assessment of electricity infrastructure. The indicators represent the potential for electricity supply disruption across different risk levels, providing a quantitative synthesis of the spatial hazard and vulnerability results.

These aggregated metrics translate spatially distributed infrastructure risk into comparable disruption levels and constitute the basis for the subsequent cascading effects analysis, in which electricity-dependent assets are evaluated.

Based on these disruption indicators, a simplified economic proxy is later applied to estimate the potential order-of-magnitude economic relevance of electricity supply interruptions.

No explicit economic loss model is implemented. Instead, the assessment relies on commonly used reliability indicators — Energy Not Supplied (ENS) and Additional Generation Cost (AGC) — which approximate the magnitude of service disruption using representative assumptions for electricity demand, repair duration, and energy prices.

The objective is not precise loss quantification but comparative interpretation of the consequences of localized electricity supply disruptions.



6.1.5 Cascading effects related to the windstorms on electricity network

Cascading effects of HEAVY WIND on ELECTRICITY on Salzburg
Cascading risk assessment methodology
Cascading effects related to heavy wind events are assessed by linking potential electricity supply disruptions to dependent built assets located within affected service areas. The analysis focuses on functional impacts caused by localized electricity outages rather than direct physical damage to buildings. Electrical service areas are approximated using polygons centered on electrical substations. These areas represent zones potentially supplied by each substation and therefore areas where buildings may be affected by power supply interruptions triggered by wind-induced failures of electrical components.

Failure probabilities of individual electrical components are spatially aggregated within these service areas. By combining local hazard intensity with infrastructure vulnerability, the approach identifies zones where electricity supply disruption is more likely to occur under heavy wind conditions.

Buildings located within service areas characterized by elevated disruption probability are considered exposed to cascading impacts. The spatial overlap between electricity supply risk and the distribution of buildings provides a first-order estimation of indirect impacts under data-limited conditions.

Cascading effect results

The cascading effect results illustrate the spatial distribution of buildings potentially affected by electricity supply disruptions under heavy wind conditions. Cascading Effect Buildings and lines results shows the spatial overlap between service areas with elevated electricity supply risk (approach 1) and the distribution of exposed buildings, highlighting zones where indirect impacts may occur due to localized power outages.

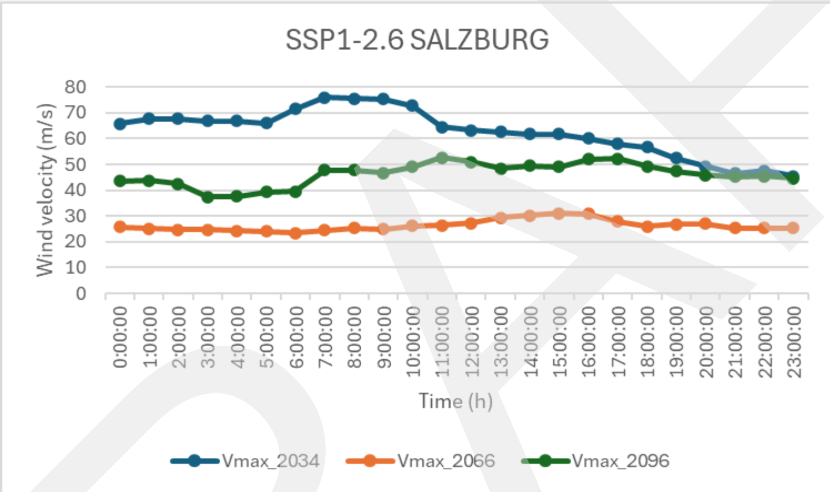
The table below summarizes the number of buildings within each cascading risk class. Most buildings fall within the high-risk category. This distribution is mainly driven by the spatial concentration of urban development within a limited number of supply zones combined with higher wind exposure along the valley floor, rather than uniformly high infrastructure vulnerability.

Level	Number of Buildings	%
No Risk	18,990	9,60
Very Low Risk	2,944	1,49
Low Risk	16,714	8,45
Moderate Risk	12,186	6,16
High Risk	147,067	74,31
Total	**197,901**	**100**

The table below summarizes the building exposure for the stress-test event (2038). The SSP1-2.6 projections (2034, 2066 and 2099) are presented in the table. The stress-test event produces substantially higher risk values, whereas the SSP1-2.6 simulations show very low and decreasing cascading risk over time.

This pattern indicates that electricity-related cascading impacts are primarily associated with rare extreme wind events rather than with gradual changes in mean wind conditions projected under the SSP1-2.6 scenario.

SCENARIO SSP1_2.6	VMAX (m/s)	VMIN (m/s)	RISK % (Approach 1)
SSP126_2034	55.3595	0.354692	0.027
SSP126_2066	22.9662	0.483233	0.000097
SPP126_2096	33.6338	0.2827	0.0028



The figure shows the temporal evolution of maximum wind speeds under the SSP1-2.6 scenario. Wind speeds (m/s) remain moderate and exhibit a slight decreasing tendency over time (h), consistent with the low cascading risk levels obtained for the future projections.

Accordingly, the associated economic impacts are negligible for the analyzed SSP1-2.6 years. This confirms that significant cascading electricity impacts in Salzburg are linked primarily to rare extreme wind events, represented by the 2038 stress-test case.

Economic impact of cascading effect CASE 2038

To complement the spatial cascading impact analysis, a simplified economic assessment is performed to approximate the potential consequences of electricity supply disruptions. The objective is not detailed loss quantification but an order-of-magnitude estimation allowing comparison between risk classes.

The economic impact is evaluated using two commonly applied electricity reliability indicators: Energy Not Supplied (ENS) and Additional Generation Cost (AGC). These indicators translate the number of affected buildings into an estimate of unmet electricity demand and associated supply costs during outage conditions.

Energy Not Supplied is estimated as the product of the number of affected buildings, an average electricity demand per building, and an assumed repair duration:

$$ENS = N_{buildings} \cdot E_{avg} \cdot t_{repair}$$

where $N_{buildings}$ represents the number of buildings exposed to potential electricity supply disruption within each risk class, E_{avg} is the average electricity demand per building, and t_{repair}}is the assumed average repair time.

The corresponding economic impact associated with unmet electricity demand is then approximated as:

$$C_{ENS} = ENS \cdot P_{elec}$$

using an average electricity price of 0.13 €/kWh, representing a typical end-user electricity cost.

In addition, potential costs associated with temporary alternative electricity supply are approximated through the Additional Generation Cost (AGC). This indicator represents the cost of supplying electricity through diesel-based or other backup generation systems during outage periods and is calculated as:

$$C_{AGC} = N_{buildings} \cdot E_{avg} \cdot t_{repair} \cdot P_{diesel}$$

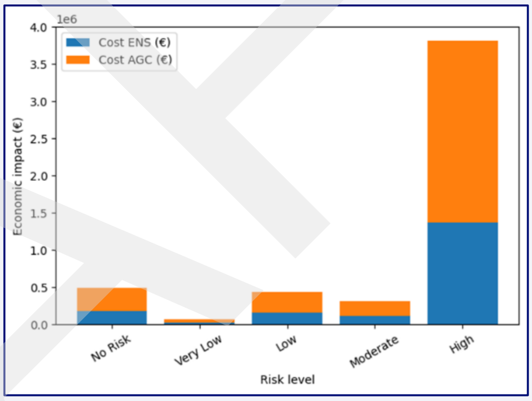
where P_{diesel} is assumed to be 0.23 €/kWh, reflecting representative costs of electricity generation using diesel-based systems.

The economic assessment represents an order-of-magnitude estimate intended for comparative analysis across risk classes rather than detailed sector-specific loss quantification. Despite its simplified formulation, it provides a consistent framework to evaluate the relative importance of cascading electricity disruptions within the study area.

The resulting indicators enable comparison between spatial risk levels and highlight the potential significance of indirect impacts beyond direct physical damage to electricity infrastructure.

Risk Level	Number of Buildings	ENS (kWh)	Cost ENS (k€)	Cost AGC (k€)
No Risk	18,990	1,367,280	177,746	314,474
Very Low Risk	2,944	211,968	27,556	48,752
Low Risk	16,714	1,203,408	156,443	276,784
Moderate Risk	12,186	877,392	114,061	201,800
High Risk	147,067	10,588,824	1,376,547	2,435,429
Total	**197,901**	**14,248,872**	**1,852,353**	**3,277,239**

The table above shows that economic impacts are strongly concentrated within the high-risk areas. Most of the estimated unmet electricity demand and associated costs originate from a limited portion of the study area characterized by elevated disruption probability.

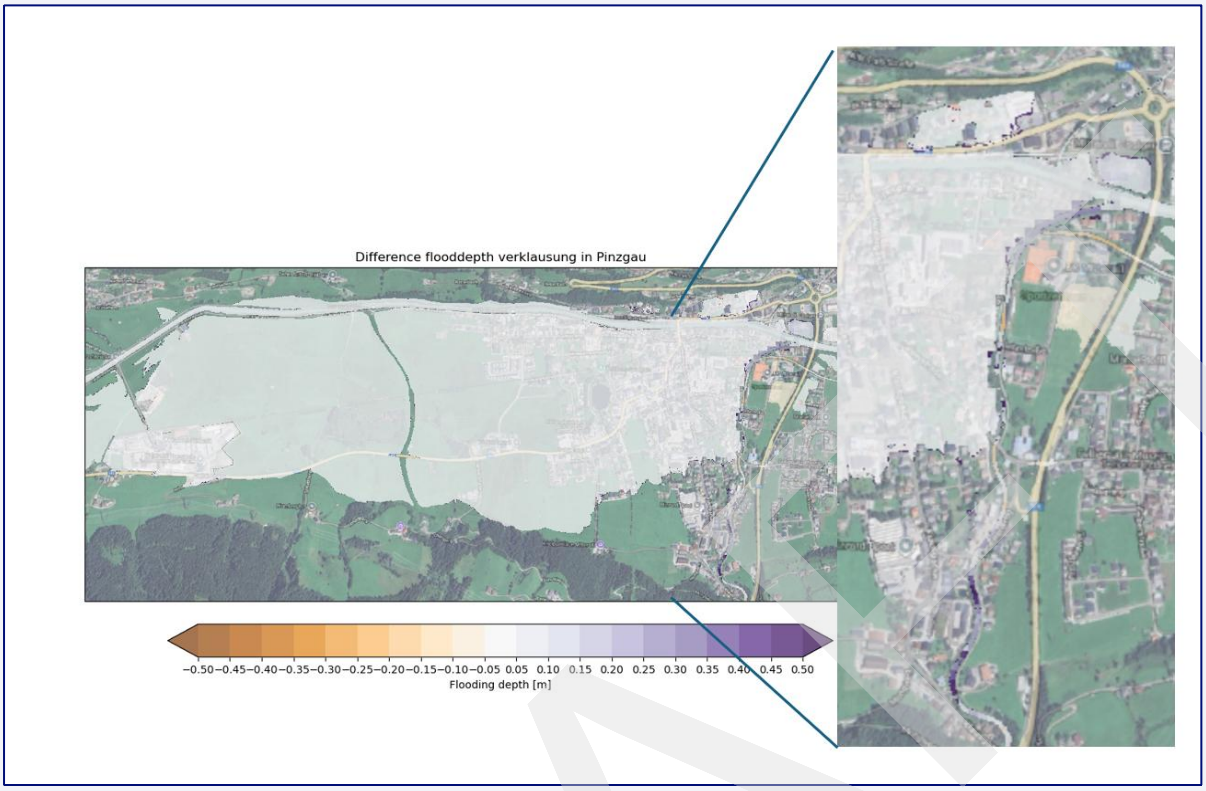


For the SSP1-2.6 scenario, failure probabilities remain very low, resulting in negligible ENS and economic losses. This confirms that cascading electricity impacts in Salzburg are primarily driven by rare extreme wind events rather than by gradual climatic changes in average wind conditions.

6.2 Multi-hazard risk assessment

6.2.1 Multi-hazard risk computation & conclusion

Risk assessment of FLUVIAL FLOODS & WINDSTORMS on PROPERTIES
Risk assessment methodology
To assess the compound effect of storm and fluvial flooding, the impact of broken trees and other debris on the flood depth is assessed. Therefore, the manning coefficient, that represents the smoothness of rivers, was adjusted within the whole domain. In the single hazard simulations, a manning coefficient for a clean river was assumed, representing the main river Salzach and its incoming streams, while in the multi-hazard simulation a high Manning coefficient (0.06) was applied. Since the Salzach and its incoming streams are bordered by trees, the streams even more than the Salzach, the assumption of fallen trees blocking the flow is justified. Consequently, the risk on properties is simulated the same way as in the single hazard risk assessment.
Hazard assessment of WINDSTORMS and FLOODS
The multi-hazard flood risk was computed with the SFINCS model, but assuming a higher manning coefficient, as stated above. The value (0.06) was chosen based on suggestions for flow in open channels as well as the minimum and maximum values suggested on the SFINCS manual. As a sensitivity test, the simulations were also performed with a value of 0.1, yet the results didn't differ significantly. For interpreting the results, it is important to note that there are no bridges in the Mittersill area that are in danger of being blocked due to debris because the two bridges over the main river Salzach don't have any pillars within the river, one even being a lifting bridge. The resulting river height and related flood depth of the Salzach displays no change between the experiments with a smooth flowing river and the multi-hazard scenario. This is due to different reasons: the riverbed is relatively wide and deep, thus debris due to trees and bushes doesn't strongly alter the flow, further, there are no bridges in danger of being blocked that would consequently present a substantial barriers and finally the blocking of the incoming streams slows the incoming water and reduces its volume. However, the incoming stream in the south of Mittersill displays changes in flood depth due to the increased blocking with a slight increase of 0.5m flood depth for a 100yr return period event. Only this one is evaluated in detail as no significant changes are seen in the others.



Difference of Flood depth for a 100yr RP event under SSP5-8.5 between single and multi-hazard simulation (manning coefficient adapted)

Exposure assessment of PROPERTIES

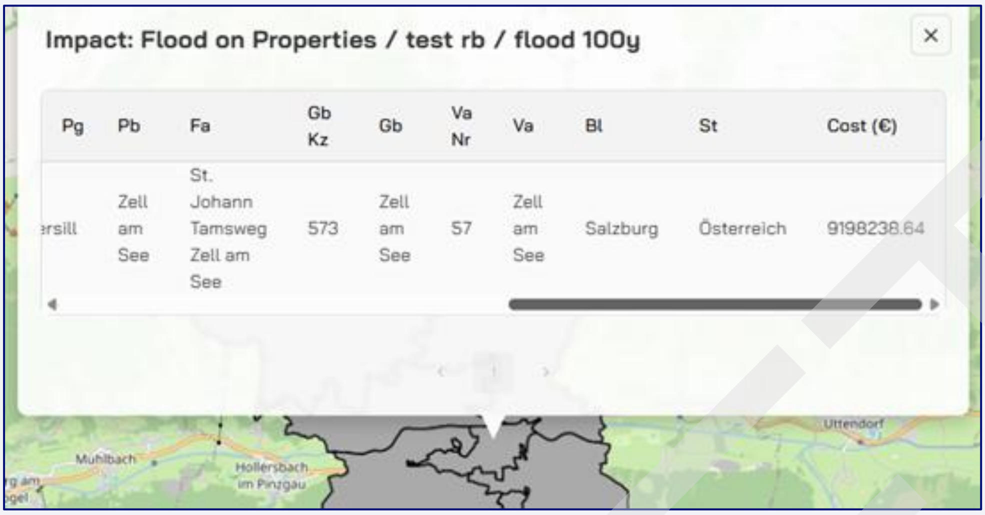
The exposure of properties of the Mittersill region is characterized by the locations and area of buildings in the studied area, based on the information stated in the section "flood risk on properties".

Vulnerability assessment of PROPERTIES

Vulnerability of buildings as in damage due to flood depth was assessed using the generalized vulnerability curves based on Huizinga et al. (2016) available within the DSS.

Impact assessment results

Since the flood map shows very limited effect, only along the incoming small stream without affecting the residential areas, the damage computation results in the same values as before for the 100yr SSP5-8.5 event.



Impact: Flood on Properties / test rb / flood 100y

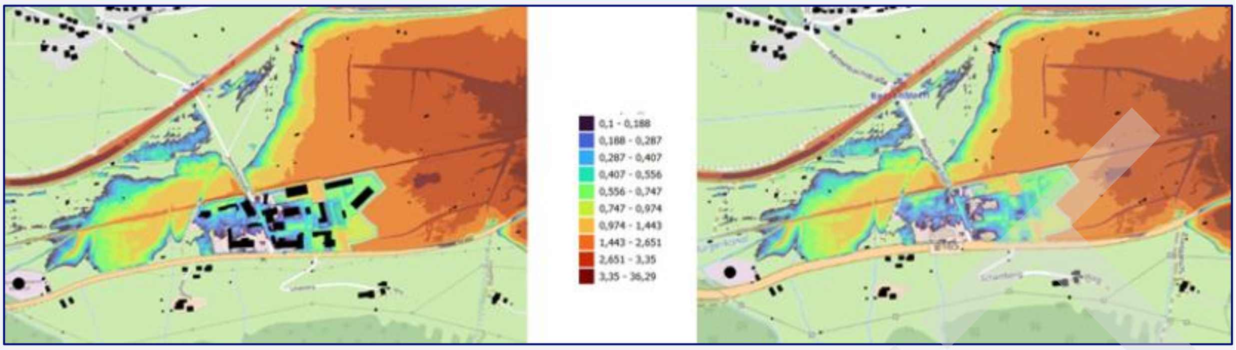
Pg	Pb	Fa	Gb Kz	Gb	Va Nr	Va	Bl	St	Cost (€)
ersill	Zell am See	St. Johann Tamsweg Zell am See	573	Zell am See	57	Zell am See	Salzburg	Österreich	9198238.64

As stated above, the simulations that reflect an increased debris inflow into streams and the river Salzach only display a small change in stream height without any relevant effect on the flood map. Therefore, the multi-hazard risk assessment on traffic is not displayed. The minimal differences are explained by the man-made adaptations to the Salzach and incoming streams over the past decades that ensure a wide and deep riverbed as well as no bridge' pillars within the river.

6.3 Adaptation scenario risk assessment

6.3.1 Adaptation scenario fluvial flooding on properties

Adaptation scenario risk assessment of FLUVIAL FLOODS on PROPERTIES
Adaptation scenario risk assessment methodology
For adaptation against fluvial flooding house relocation located within the flood prone area, as indicated by the hazard zonal maps, was assumed, building on the fact that this site is controversially discussed and to provide insights to stakeholders on the potential reduction of damage in case these buildings are relocated.
Adaptation scenario exposure assessment of PROPERTIES
To represent the relocation of the industrial assets, they were removed from the exposure file.



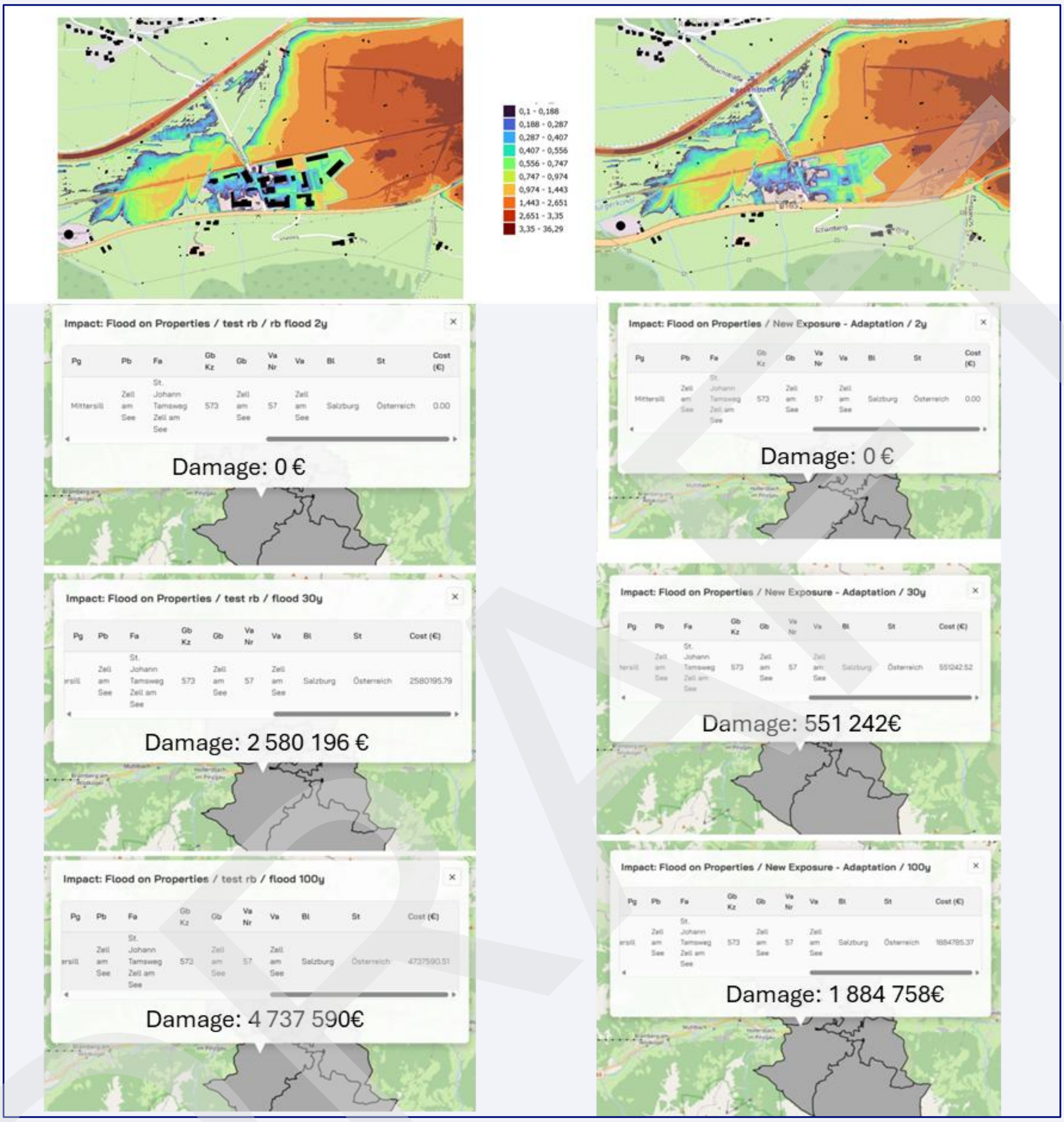
The figure shows part of flood map with buildings as status quo (left) and buildings removed within the adaptation scenario (right)

Vulnerability assessment of PROPERTIES

Vulnerability of buildings as in damage due to flood depth was assessed using the generalized vulnerability curves based on Huizinga et al. (2016) available within the DSS. Since the majority of buildings in Mittersill are residential and no specific information on building use is available, the vulnerability curve representative of residential buildings was applied.

Impact assessment results

To evaluate the effect of the measure, the same flood depth maps were taken as in the single hazard assessment, but this time the damage was computed using the adapted exposure file. The results indicate a substantial decrease in damage of about 2 M€ for events with a return period of 30 yrs. and longer.



The figure above shows damage assessment for left the single hazard assessment, right the adaptation scenario where relocation of buildings is assumed for the census region “Schattberg”.

6.3.2 Adaptation scenario fluvial flooding on transport

Adaptation scenario risk assessment of FLUVIAL FLOODS on TRANSPORT

Adaptation scenario risk assessment methodology

For adaptation of traffic interruption with respect to fluvial floods, the successful application and take up of early warning was assumed, resulting in a considerably smaller number of cars being on the street.

Adaptation scenario exposure assessment of TRANSPORT

The exposure is kept constant with respect to the single hazard assessment, the street being affected by flooding.

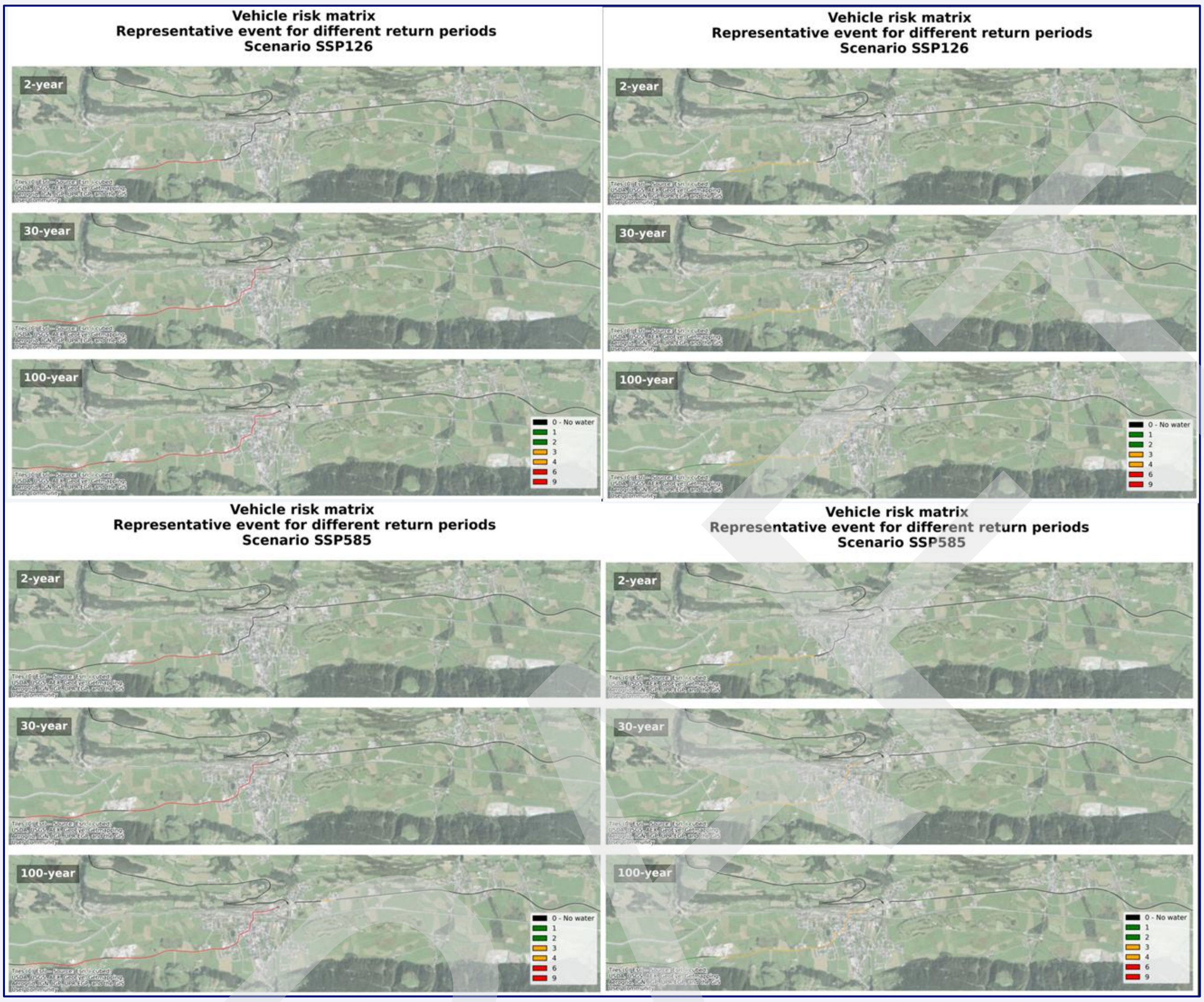
Vulnerability assessment of TRANSPORT

Vulnerability index/score	Vehicle flow intensity (VFI) (veh/day)
1 (Low)	< 5,000
2 (Medium)	5,000 ⩽ x ⩽ 10,000
3 (High)	> 10,000

The measure assumed represents early warnings, that result in a reduction of cars being on the street. Therefore, the lowest vulnerability class was taken for the risk computation.

Impact assessment results

The main effect of an early warning system is the awareness of people of an extreme event occurring and its implications. Therefore, if an early warning on flood is issued, two actions can be taken: blocking of streets that are susceptible of flooding by public authorities, or reduced car traffic due to people avoiding trips. In both cases the disruption and consequently damage of flooded cars on the evaluated streets is strongly reduced in comparison to the single hazard assessment (figure below). With only a short part of the street still representing medium effectiveness.



6.3.3 Adaptation scenario windstorm on properties

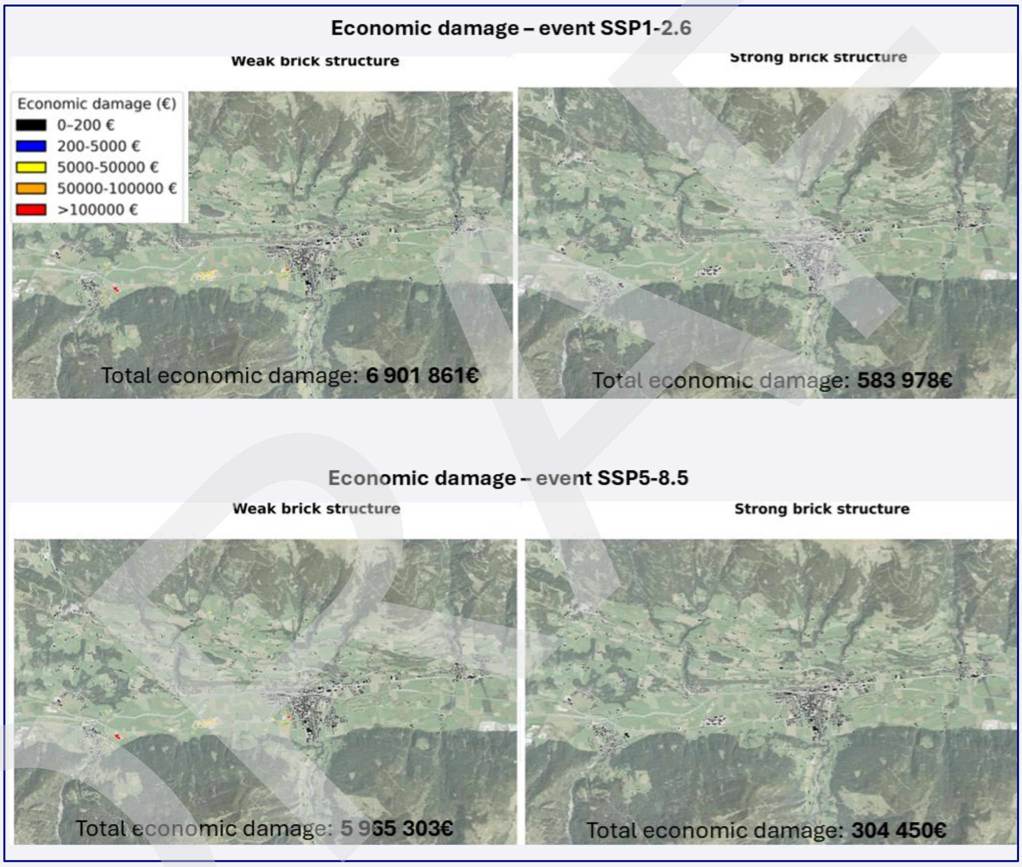
Adaptation scenario risk assessment of WINDSTORM on PROPERTIES
Adaptation scenario risk assessment methodology
To better withstand windstorms, building regulations and adaptation of norms are key. For Salzburg, it is assumed that building regulations are further enhanced, leading to more robust houses. Thus, it is assessed how the improved building structure affects economic damage. This assessment is performed for the wind speed as simulated by the model, but also for higher wind speeds. Thus, the wind speed of each grid cell was multiplied by 1.5 as a sensitivity analysis to account for the fact that local convective storms and related gusts are not covered by the climate models.
Adaptation scenario exposure assessment of PROPERTIES
The exposure is kept constant with respect to the single hazard assessment (same distribution of buildings).

Vulnerability assessment of PROPERTIES

Within these simulations the building structure "strong brick building" is assumed for all buildings present in the Mittersill region, compared to "weak brick building" in the single hazard assessment. Additionally, the effect of decreased vulnerability is analyzed for two wind events, the one as simulated within the model and a sensitivity experiment with 1.5 times the wind speed.

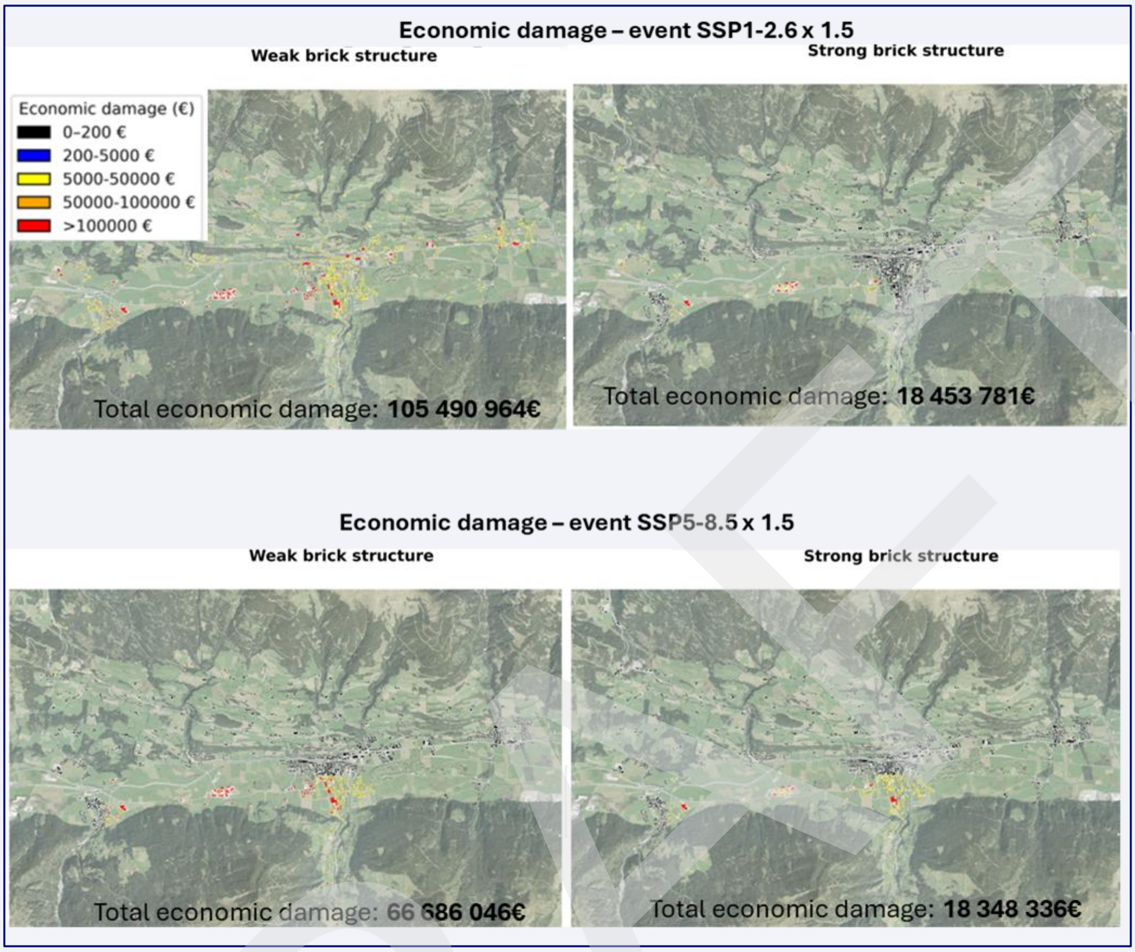
Impact assessment result

Comparing the economic damage due to the windstorms for SSP1-2.6 and SSP5-8.5 (event chosen based on highest damage caused), we find that increasing building standards to represent strong brick structure decreases the damage in both cases from about 6 to 7 Million Euros to 300.000 to almost 600.000€, thus decreasing it by 90 - 95%.



The figure above reflects the total economic damage as simulated for the single hazard assessment (left column) and with increased building standards (right column). Top: most impactful event SSP1-2.6, bottom: most impactful event SSP5-8.5.

Additionally, the sensitivity experiment displays that in case of higher wind speeds, the damage is much higher than the increase in wind speed, representing the logarithmic shape of the vulnerability curve. Yet, also in this case, increasing building codes results in a damage reduction of about 70 - 80%.



The figure above shows the total economic damage as simulated for the sensitivity experiment assuming higher wind speeds (simulated * 1.5). Comparison of the non-adapted assessment (left column) and with increased building standards (right column). Top: most impactful event SSP1-2.6, bottom: most impactful event SSP5-8.5.

6.3.4 Uncertainty assessment

For the risk assessment of the SBG case study the dynamical downscaled climate simulations for two SSP scenarios based on 2 different global climate models and 2 different regional climate models were used. This was done in order to achieve more insights into possible future conditions. 2 simulations per SSP don't represent an ensemble, yet, since these simulations are initiated with CMIP6 global climate models and were made available much earlier than the CORDEX results (Katragkou et al., 2024), these simulations provide crucial first updates.

Within Bügelmayer-Blaschek et al., 2025 we validated and compared the available statistical versus the dynamical one and found that, especially for the hazards relevant for the trials, the dynamical downscaling provided better insights.

With respect to the investigated hazards: fluvial flooding caused by precipitation and windstorms, we find similar trends in both models and SSPs. The absolute values differ, for instance the MPI-ESM-HR driven WRF simulation results in overall higher wind speeds than the EC-EARTH-Veg3 driven CLM one, but both models display a very moderate increase in intensities. To assess the impact, we used all model data, yet, within this deliverable we focused on the maximum events, since the focus is to better understand and provide guidance on adaptation towards extreme (multi-) hazards.

For the flood map we used the SFINCS model and supported its adaptation to application in mountainous regions through intense exchange with the developers. Yet, due to time and data constraints, the final flood maps display too high flood depths in the center of Mittersill, as stated also above.

Apart from uncertainty in hazard data, for Salzburg we encountered the problem of having specific damage data. Therefore, we used available vulnerability curves and cost estimates, that enable a first assessment of the potential risk, but need further improvement for more targeted risk assessment.

Nonetheless, the workflow set-up, as well as the results compiled provide a valuable base for future work and already initiated discussions within the CoP.

7 SAR Risk assessment results

7.1 Single-hazard risk assessment

7.1.1 Risk assessment of wildfires in Rhodes

The economic wildfire risk assessment on the CI of Rhodes Trial is the combined risk of the buildings, road network, and powerline grid of the island. The combined risk of these assets has a direct economic impact. To facilitate analysis, we designate these assets as economic.

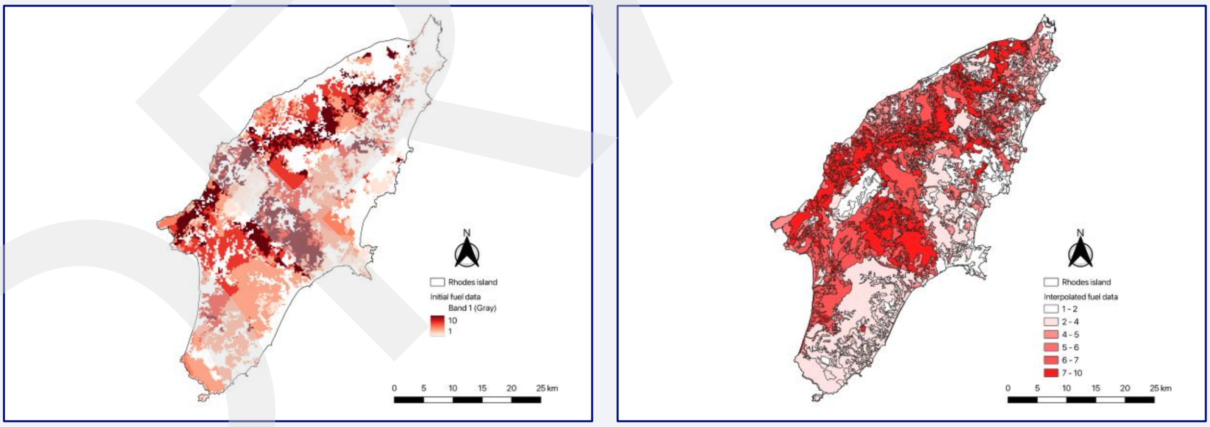
Risk assessment of WILDFIRES in RHODES

Risk assessment methodology

Following the methodology presented in Section 4.2.3, and the wildfire hazard, the wildfire risk assessment continues with the steps below.

Hazard calculation - FWI and high accuracy Fuel type maps

For the wildfire risk assessment, the hazard is defined as a combination of the Fire Weather Index (FWI) and the Fuel Type maps from EFFIS. The existing EFFIS fuel map, for the area of interest, has extensive data gaps, partially covering the total extent of the case study area. To address this issue, the available data were interpolated to minimize the data gaps, based on the Corine Land Cover (CLC) dataset. The interpolation results are presented in the figure below and the link-up table between the CLC and FT data is presented in the table below.



(Left) Original Fuel type map, (Right) Updated Fuel type map covering the full extent of the case study area.

CLC code	Fuel type
112, 122, 123, 124, 142, 331, 333, 512	1
121	2
231	3
131, 133, 311, 311	4
222, 242, 323	5
221	6
141, 223, 243, 324	7
312, 313	10

Exposure and Vulnerability calculation

The vulnerability is categorized in three categories: economic, ecological, and people. The economic vulnerability covers the majority of the CI in the case study area (road network, power distribution network, and buildings), the ecological based on the CLC categories, and the people based on the population density of the case study area. Each vulnerability category is categorized into 5 classes, with the score increasing expressing increasing vulnerability.

Score	Economic (M€)	Ecological (CLC code)	People (people/km2)
1	< 2.7	335, 512	< 8
2	2.7 – 54	331, 332, 411, 412, 421, 422, 423	8 -17
3	54 – 81	111, 112, 121, 122, 123, 124, 131, 132, 133	17 – 25
4	81 – 108	211, 212, 213, 221, 222, 223, 231, 241, 242, 243, 244	25 – 35
5	> 108	311, 312, 313, 321, 322, 323, 324, 334	> 35

Risk calculation

The wildfire risk is calculated and categorized based on the scoring system used for hazard, exposure and vulnerability, described above. For each of the vulnerability categories, the risk ($Risk_i$) is calculated as the product of the hazard, exposure and vulnerability score by Eq. 1. The total risk

($Risk_{tot}$), is calculated with emphasis on the risk of local population, as shown in Eq. 2. (Oom et al., 2022)

$$Risk_i = Hazard_i \times Exposure_i \times Vulnerability_i \qquad (1)$$

$$Risk_{tot} = 0.5Risk_{pop} + 0.25Risk_{ecol} + 0.25Risk_{econ} \qquad (2)$$

where: refers to the risk categories: for people, for ecological, and for the economic risk.

7.1.2 Risk assessment of wildfires on economic assets.

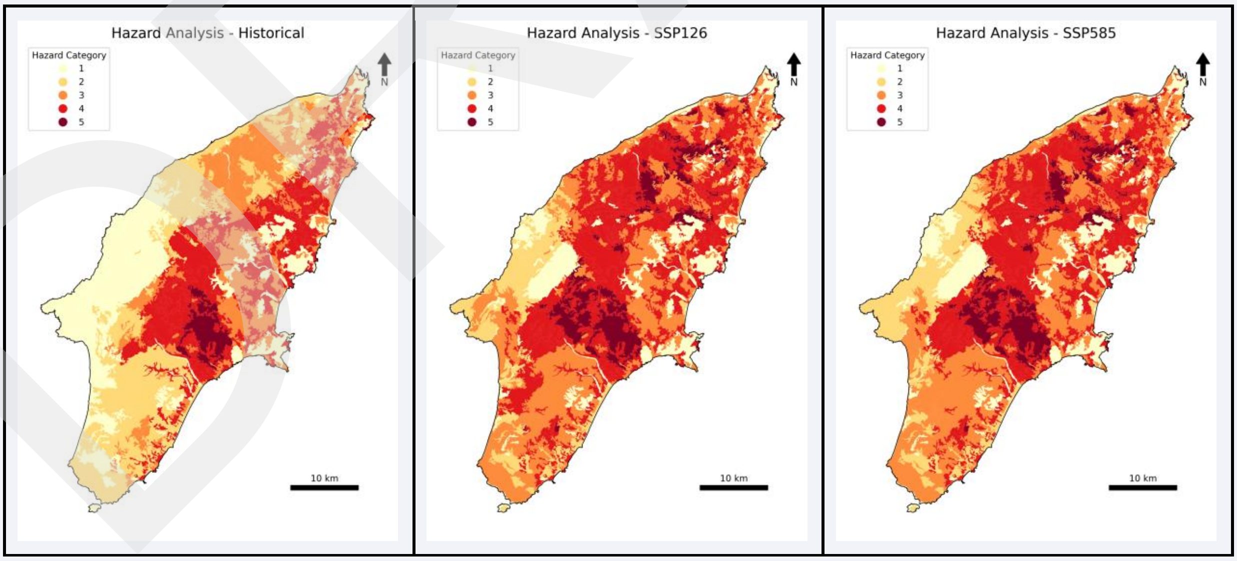
Risk assessment of WILDFIRES on ECONOMIC ASSETS

Risk assessment methodology

This assessment's goal is evaluating the potential economic damages to properties on the island of Rhodes. As presented above, Section 4.2.3, risk framework combines hazard, exposure, and vulnerability components to estimate the wildfire risk of the buildings. The assessment was done for different scenarios to see the evolution of the wildfire risk between them.

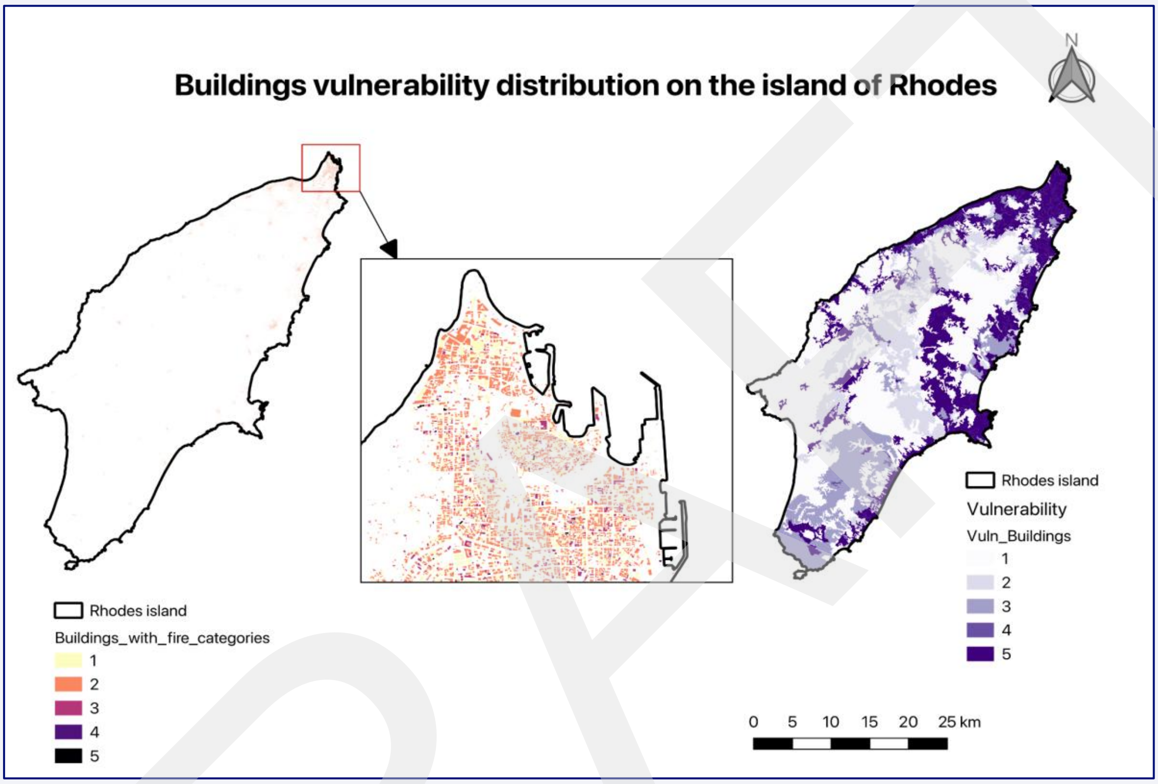
Hazard assessment on ECONOMIC ASSETS

The wildfire hazard is based in the FWI on the island of Rhodes. As shown in the left figure, the wildfire hazard is increasing in the future scenarios, in comparison with the historical data. The same observation can be made for the wildfire exposure (right figure), as it is calculated with the addition of the FT map.



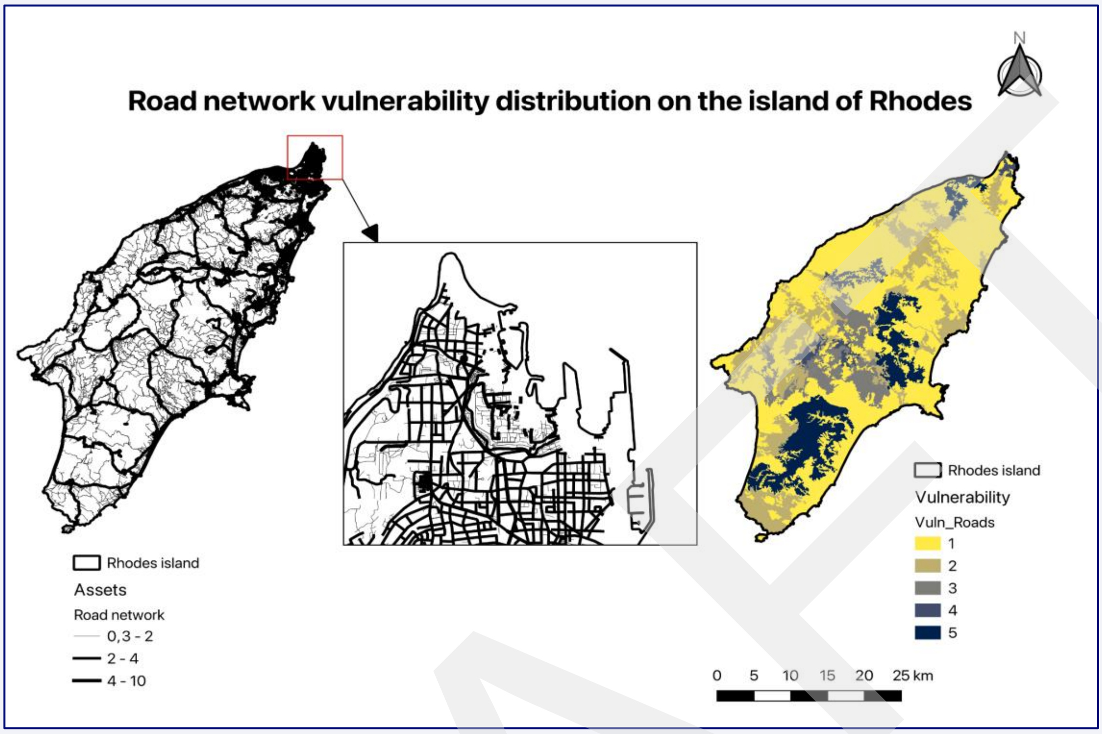
Vulnerability assessment on BUILDINGS

The buildings' vulnerability was based on the construction material. This was used to categorize the individual building vulnerability. Based on the resolution of the risk assessment and the extent of the Trial region, the individual vulnerability was normalized to the building density, since this is another parameter that affects the buildings' vulnerability. These analysis results are presented in the map below.



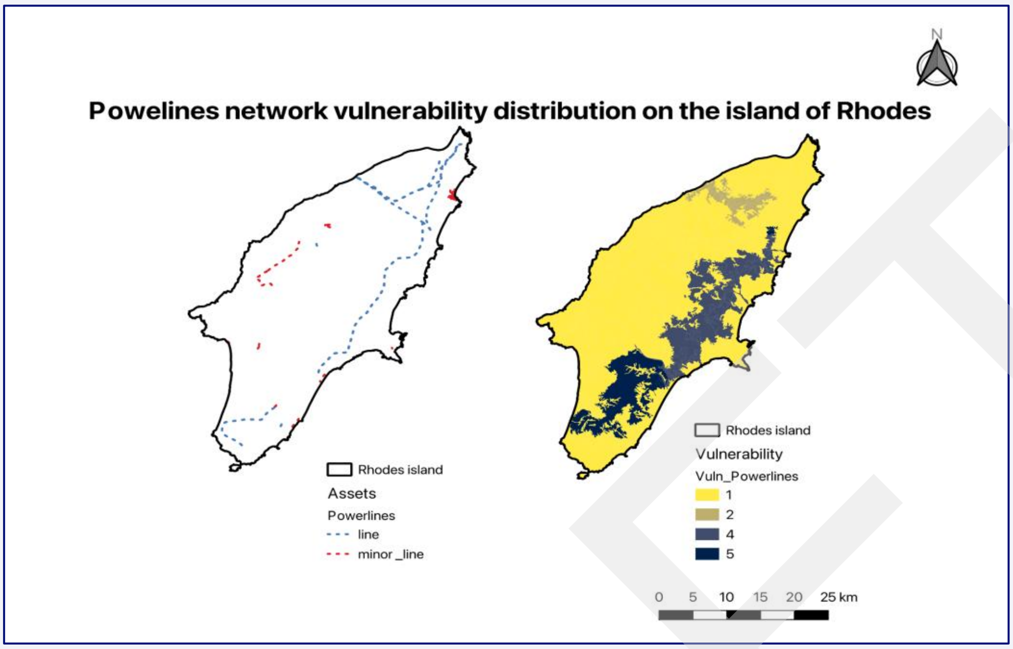
Vulnerability assessment on ROAD NETWORK

The road network vulnerability was based on the road width. This was used to categorize the individual road section vulnerability, mainly due their transport capacity. Based on the resolution of the risk assessment and the extent of the Trial region, the individual vulnerability was normalized to the road network density, since this is another parameter that affects the road network' vulnerability. These analysis results are presented in the map below.



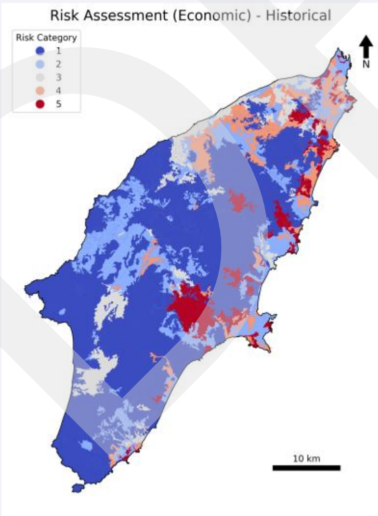
Vulnerability assessment on POWERLINES

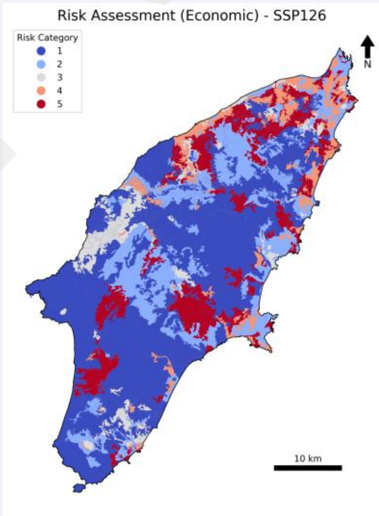
The powerline network vulnerability was based on the high voltage powerlines categories. This was used to categorize the individual powerlines section vulnerability, mainly due their power capacity. Based on the resolution of the risk assessment and the extent of the Trial region, the individual vulnerability was normalized to the powerlines network density, since this is another parameter that affects the powerlines' vulnerability. These analysis results are presented in the map below.

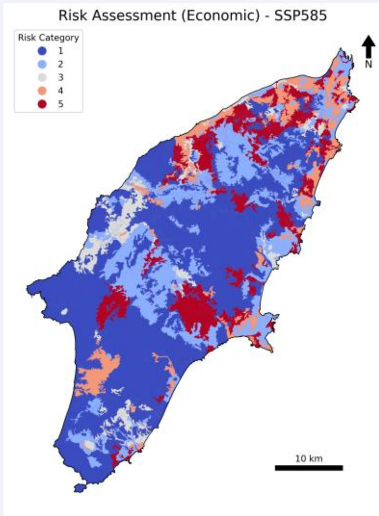


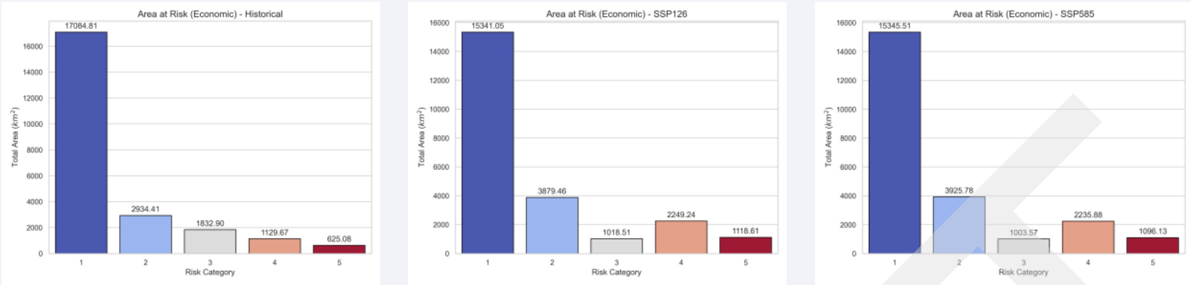
Risk assessment results

Rhodes' economic risk profile shows a mix of high and moderate risk. Category 1 (dark blue) covers large parts of the island, especially in the west and south. Meanwhile, categories 2 (light blue) and 3 (grey) are spread across central and northern regions, indicating moderate exposure to fire risk. The distribution suggests that key areas—such as the electricity network, roads, and residences—are scattered across zones with varying vulnerability levels. Patches of category 3 and occasional category 4 (orange) areas highlight sectors with higher wildfire hazards. Under the SSP126 scenario, socio-economic risk rises significantly, with more extensive category 3 and 4 zones, especially in central and northern areas. The increase in orange patches shows that, under moderate climate change, many economically vital areas could face greater wildfire threats, affecting agriculture, power, transportation, and tourism. Similar trends are seen in SSP585, with increased risk in smaller western regions.



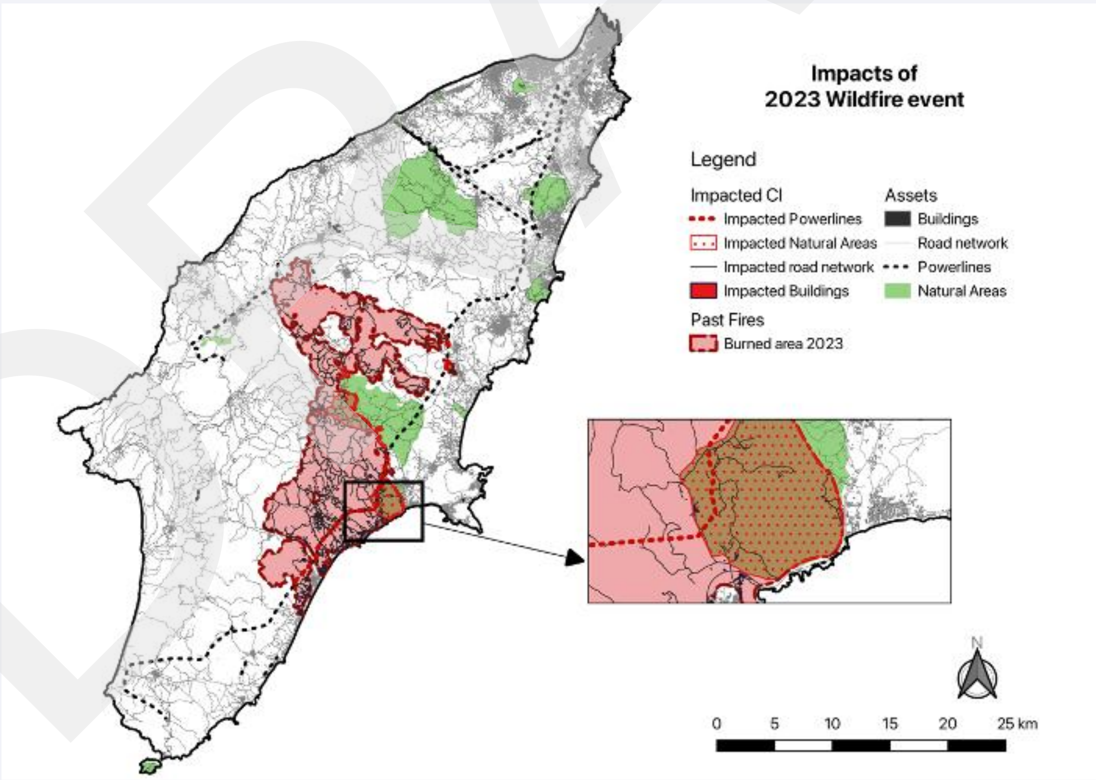






Impact assessment methodology

In 2023, the island of Rhodes suffered a 10-day wildfire event that caused extensive damage to over 17.600 acres. This event was used for the wildfire impact assessment of Rhodes Trial. The extent of the burned area is presented in red color. The event had a significant economic impact on the power distribution network and a few homes. According to the Greek Electricity Distribution Network operator, 15 km of powerlines, 110 poles, and 3 substations were completely damaged. This caused a total loss of service in the affected areas for the first 24 hours, with full repairs taking several days afterwards. The total cost for repairing the electricity grid amounted to €1.289.000. Additionally, the water distribution network damage was estimated at €400,000, with another €150,000 needed for emergency leasing of a desalination unit and power generators to meet urgent water needs in affected settlements. The Civil Protection reports also indicated the total destruction of 6 houses and partial damage to 39 others. Agriculture was the most severely impacted sector, with nearly 2.500 livestock lost, excluding wildlife. Approximately 60.000 olive trees and 20.000 other crops were burned, resulting in repair costs around € 4,000,000 for the agricultural sector.



7.1.3 Risk assessment of wildfires on the ecology

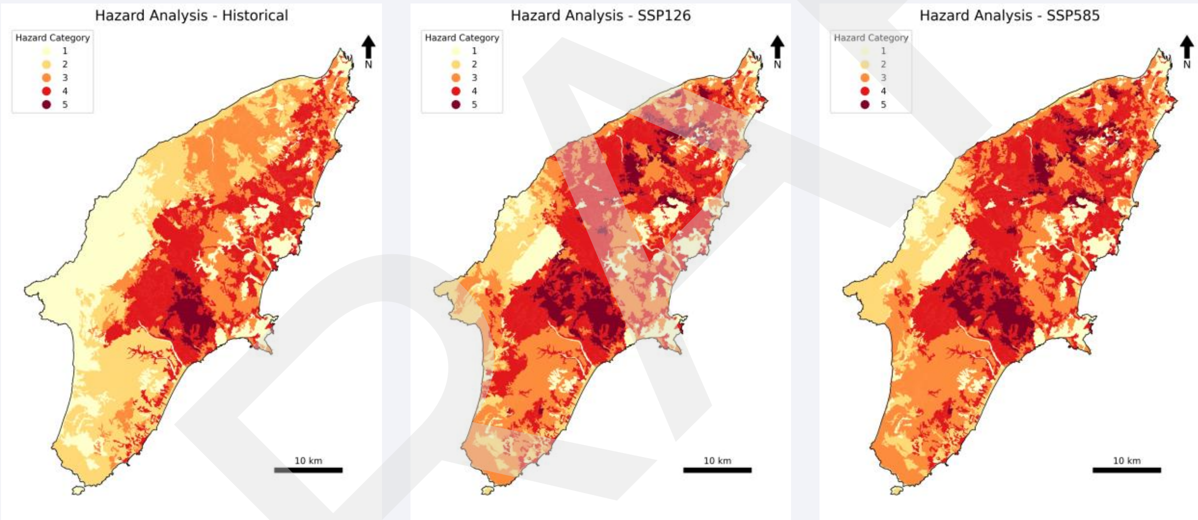
Risk assessment of WILDFIRES on ECOLOGY

Risk assessment methodology

As presented above, Section 4.2.3, risk framework combines hazard, exposure, and vulnerability components to estimate the wildfire ecological risk. The assessment was done for different scenarios to see the evolution of the wildfire risk between them.

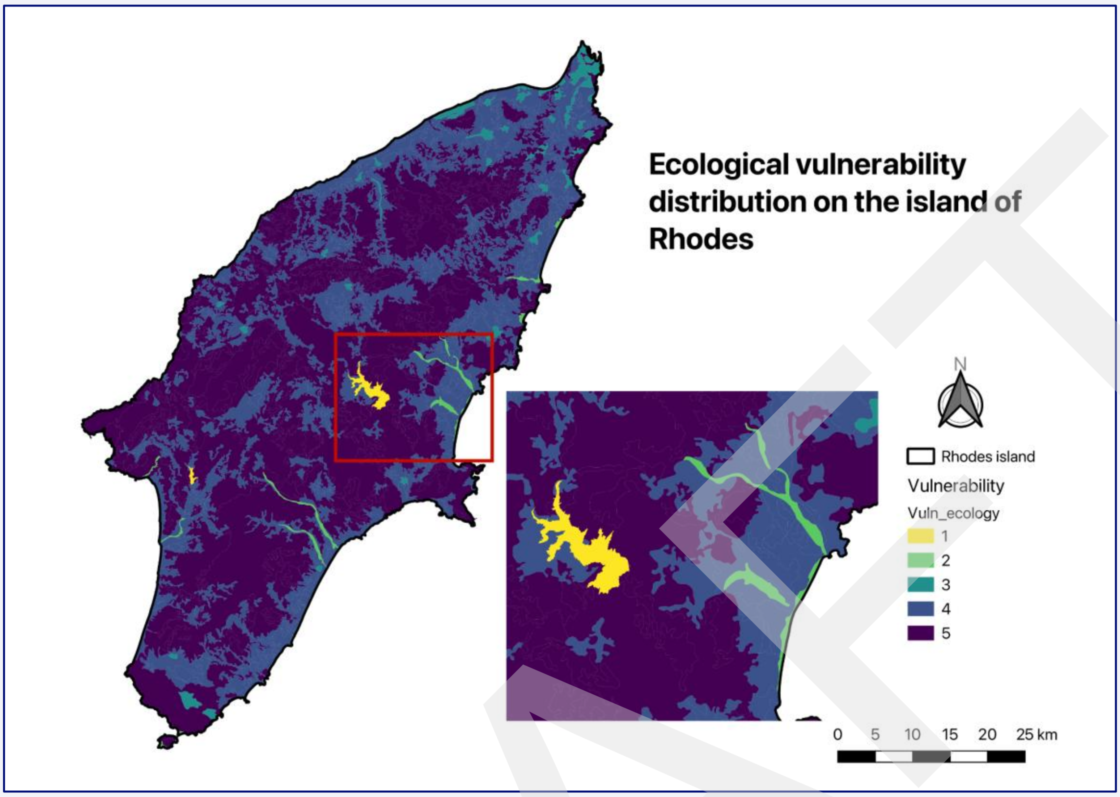
Hazard and Exposure assessment on ECOLOGY

The wildfire hazard is based in the FWI on the island of Rhodes. As shown in the left figure, the wildfire hazard is increasing in the future scenarios, in comparison with the historical data. The same observation can be made for the wildfire exposure (right figure), as it is calculated with the addition of the FT map.



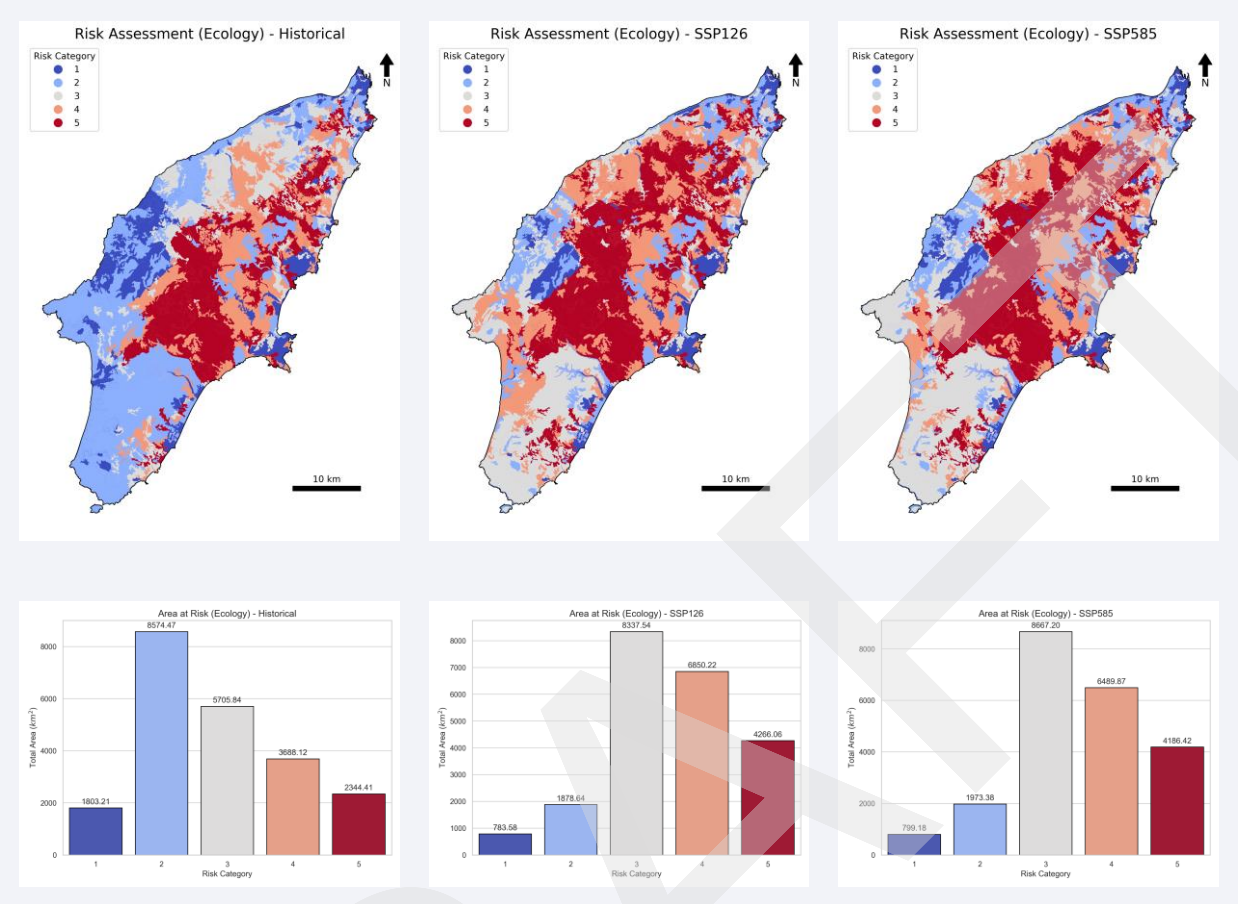
Vulnerability assessment on ECOLOGY

The ecological vulnerability is evidently high in the majority of the island. As shown, 93% of the island is characterized by a high vulnerability score (>4). These vulnerable areas are mainly due to the high coverage of the island with forested areas, marshlands, and agricultural areas. The rest of the island (7%) with vulnerability score < 4, are the urban and peri-urban areas along the coast, where the major touristic activity takes place.



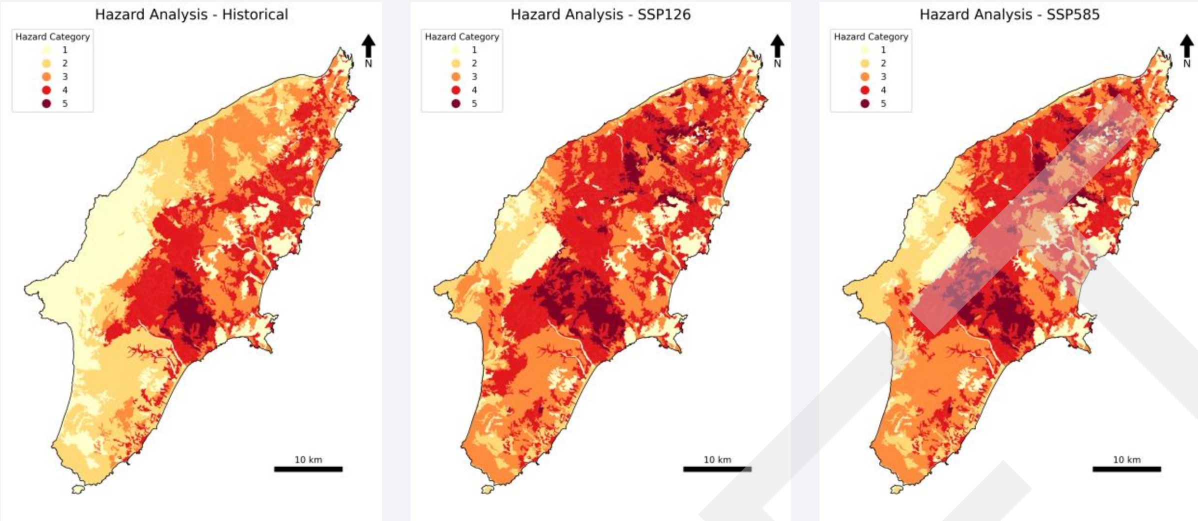
Risk assessment on ECOLOGY

Rhodes historically exhibits moderate wildfire risk mainly in its central mountainous regions, with risk scores mostly falling into categories 3 and 4 (grey to orange). Coastal and northern areas tend to show lower risk levels (categories 1 and 2, dark blue and light blue), due to less dense and different types of vegetation. Under the SSP126 scenario, which predicts moderate climate warming, ecological risk increases notably across the island; the central mountains shift to the highest risk category (category 5, red), indicating severe wildfire danger. The orange and light blue zones expand significantly, covering larger parts of the interior, implying that even with moderate warming, many areas face increased fire risk. The SSP585 scenario suggests the most severe risk, with widespread areas in the highest risk category (red, category 5) and growth of orange (category 4) zones across the island. This indicates that under high climate change, most of Rhodes's interior would be much more vulnerable to wildfires. Comparing the three maps shows a clear escalation pattern: climate change drives significant increases in ecological wildfire risk, with the persistent high-risk zones in the central areas indicating these regions inherently tend to be fire-prone, a condition that will worsen with future climate changes. This assessment underscores rising concerns about wildfire dangers in the Mediterranean, particularly after catastrophic events like the July 2023 Rhodes wildfire that burned over 17,600 hectares.



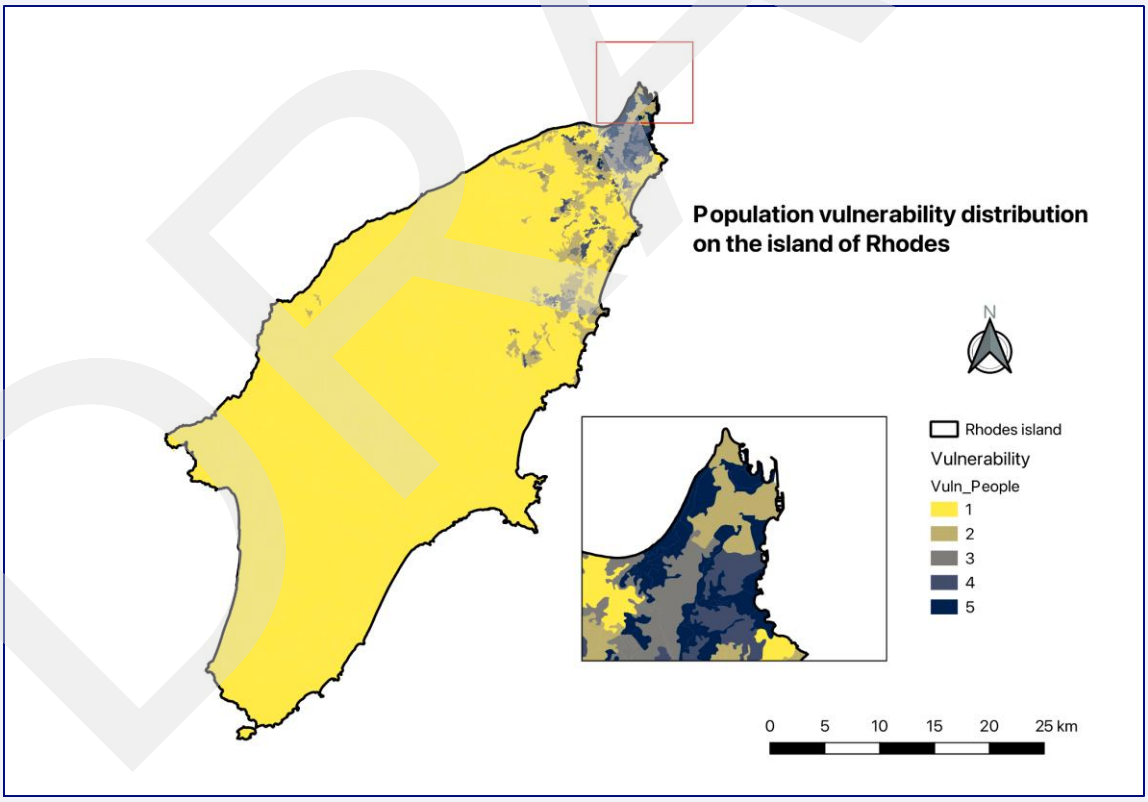
7.1.4 Risk assessment of wildfires on people

Risk assessment of WILDFIRES on PEOPLE
Risk assessment methodology
As presented above, Section 4.2.3, risk framework combines hazard, exposure, and vulnerability components to estimate the wildfire risk of the population. The assessment was done for different scenarios to see the evolution of the wildfire risk between them.
Hazard and Exposure assessment on PEOPLE
The wildfire hazard is based in the FWI on the island of Rhodes. As shown in the left figure, the wildfire hazard is increasing in the future scenarios, in comparison with the historical data. The same observation can be made for the wildfire exposure (right figure), as it is calculated with the addition of the FT map.



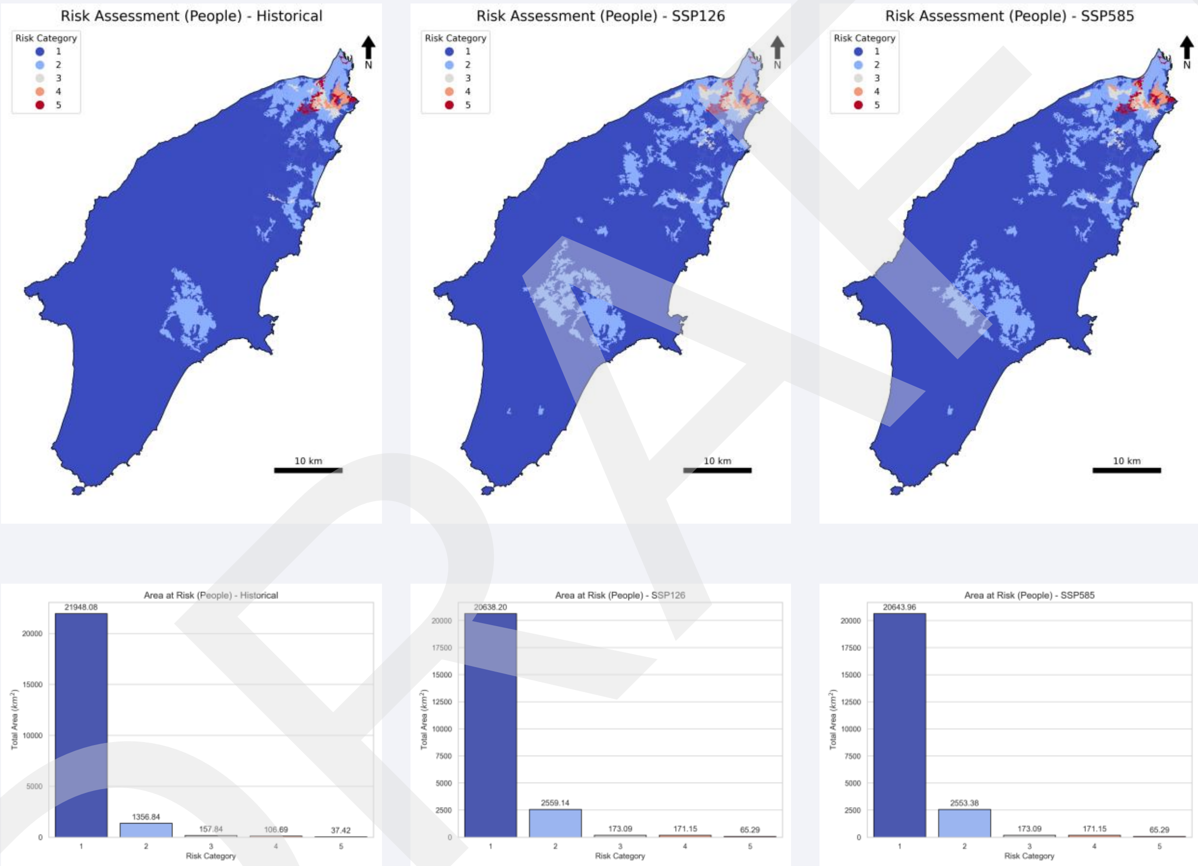
Vulnerability assessment on PEOPLE

The population vulnerability is higher on the northern part of the island, where the city of Rhodes is located. Lower vulnerability scores are identified in the coastal areas on the northeast part of the island, as well as in some places around the northwest coast. These areas are the most touristic, with a population density of more than 17 people/km^2. The rest of the island is characterized by a low vulnerability score, due to the low population density (8 people/km^2).



Risk assessment on PEOPLE

The wildfire risk to Rhodes' population under historical, SSP126, and SSP585 climate scenarios shows a generally stable but concerning pattern of vulnerability. Historically, most of Rhodes exhibits low risk (category 1, dark blue) across the island, with small patches of medium to high risk (category 4 and 5, orange and red) concentrated in certain coastal and inland settlement areas, mirroring human settlement distribution. This pattern correlates with densely populated regions near the city's administrative centre and tourist spots along the northern and eastern coasts. Under the SSP126 scenario, which indicates moderate climate warming, the risk distribution remains similar to current levels, with most areas still classified as risk category 1 and only minor patches in category 2. The SSP585 scenario, representing severe climate change, also shows predominantly low-risk (category 1) zones, with only minor increases in higher risk patches compared to the other scenarios.



Impact assessment on PEOPLE

The impact on the population, with respect to casualties, was zero, but during the 10-day period, 19.000 people were evacuated, from 11 settlements, from the area to the northern parts of the island, either by land (16.000) or sea (3.000).

7.1.5 Single hazard risk assessment - Heatwaves in Syros Island Trial

Risk assessment of HEATWAVES on BUILDINGS

Risk assessment methodology

The heatwave risk assessment on the CI of Syros Trial is focused on the buildings of the island and their capacity to cope with the extreme heat.

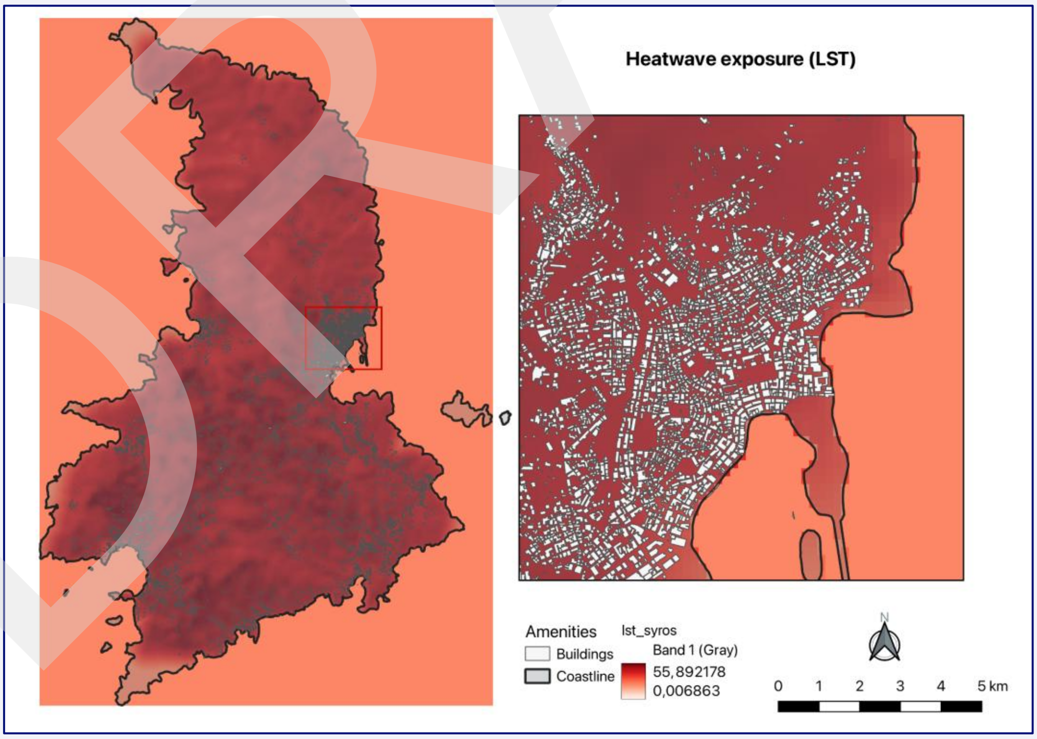
The risk assessment methodology is based on the on the equation below:

Hazard x Vulnerability = Risk

In this case as **Hazard,** we use the R50 heatwave as it is translated to land surface temperature (LST), categorized in 5 classes (see Section 4.3.3), and as Vulnerability, the construction period of the buildings and the construction regulations implemented at that period, divided in 4 classes.

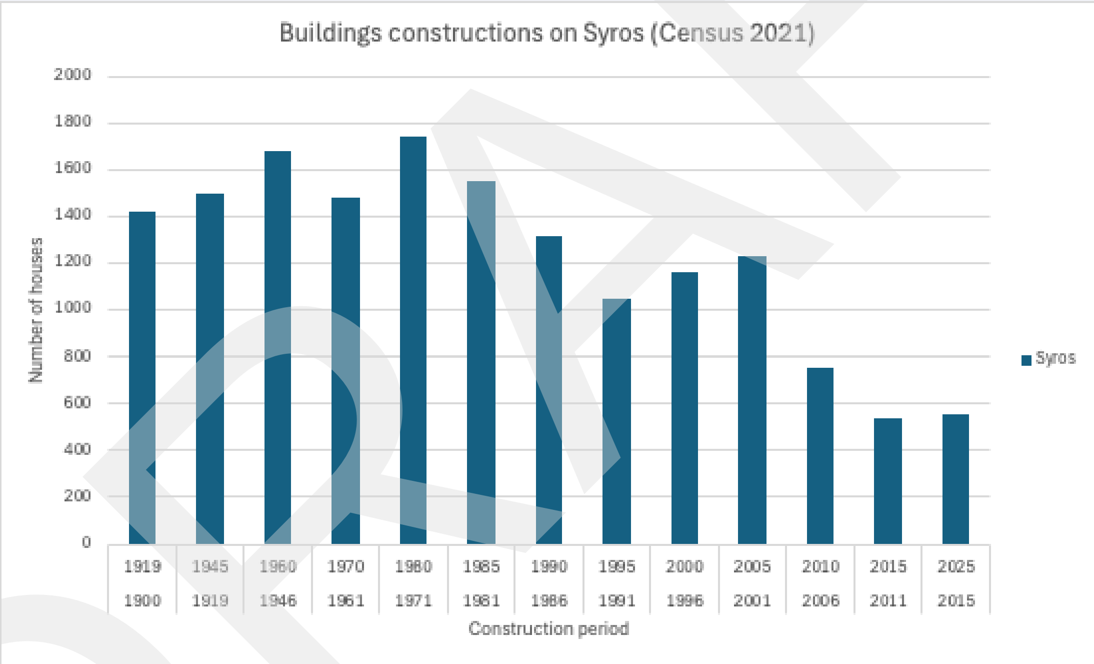
Hazard assessment on BUILDINGS

The urban heat stress conditions, relating air temperature and urban microclimate is calculated based on the Landsurface Temperature (LST) for the Trial area. This allows to identify the temperature input for indoor heat risk assessment. The scoring for this hazard component is presented in Section 4.1.



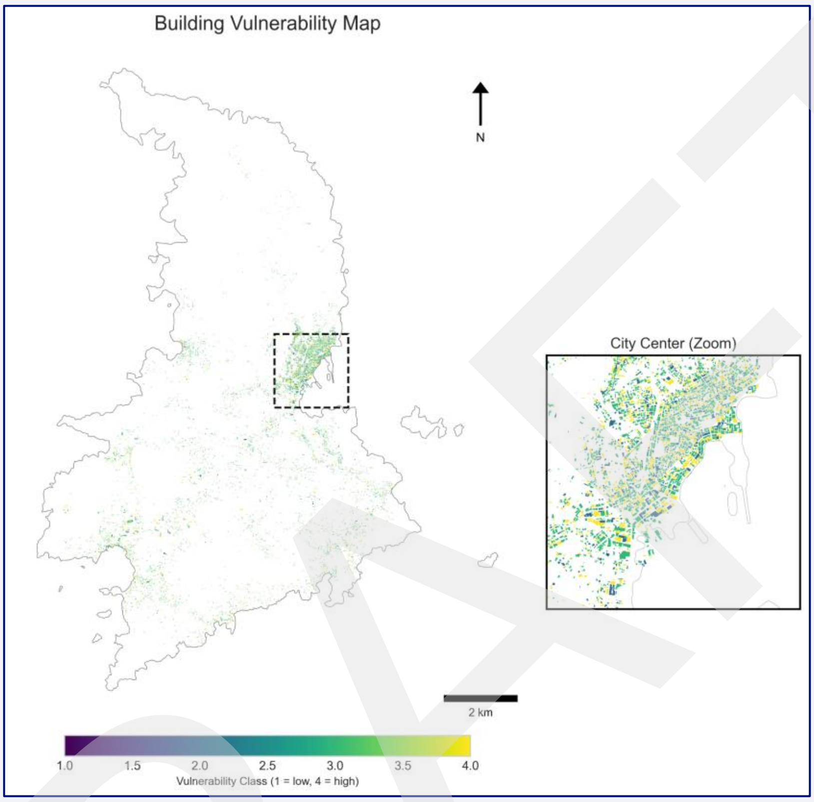
Vulnerability assessment on BUILDINGS

The buildings on the islands are categorized in four (4) classes based on their construction period. The 2021 Census reports (figure below) still standing buildings constructed prior to 1919, but most of them are limited. For the Vulnerability categorization, the buildings constructed prior to 1980 have no obligations to have any type of insulation, except from the traditional construction techniques. These buildings are typically classified in the lowest energy class (Class H) and are thermally unprotected, resulting in very high energy consumption for cooling during heatwaves and significant indoor overheating. Post 1980, the first Greek Thermal Regulation was implemented in 1981, introducing basic insulation requirements. Buildings from this era have improved, but still moderate, thermal performance compared to modern standards. Following 2010 The Hellenic Regulation on the Energy Performance of Buildings (KENAK) came into effect, requiring new buildings to meet higher energy efficiency standards (at least Class B+). Finally, Since January 1, 2020, all new buildings are required to be nearly zero-energy buildings (nZEB), effectively an "A" or "A+" energy grade, with very high thermal performance and minimal energy consumption. The scoring is presented in the table below.



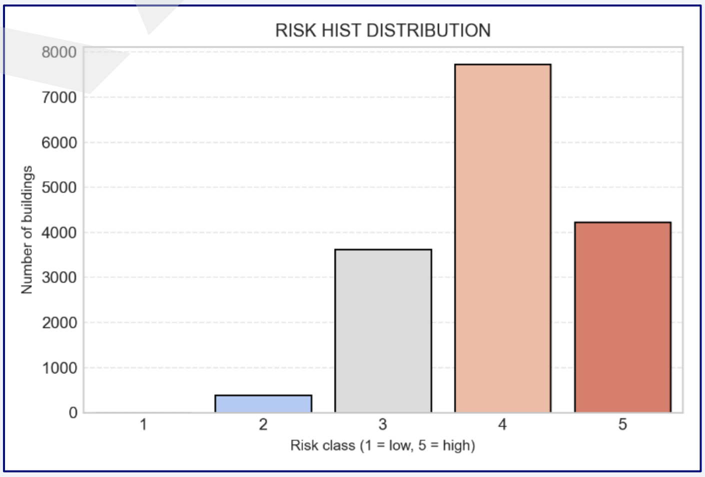
Score	Construction period
4	earlier than 1980
3	1981 - 2010
2	2010 - 2020
1	after 2020

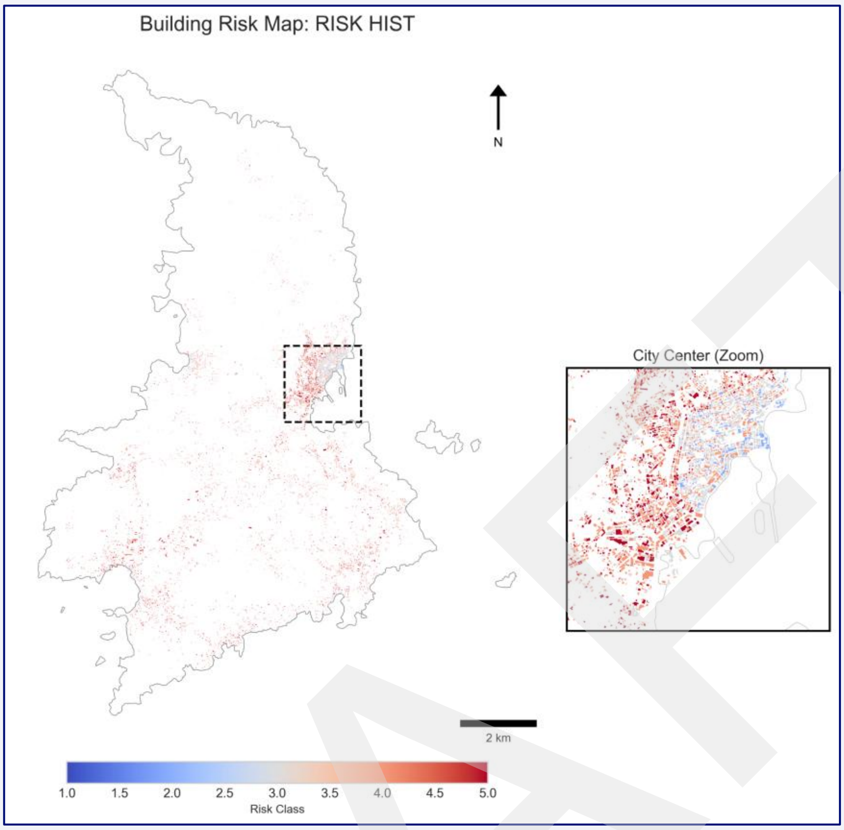
The buildings' vulnerability was based on the construction year. The buildings are divided in 4 categories based on the construction period and the national construction regulations. These regulations are defining the energy category of the buildings and consequently they are an indicator of the buildings ability to cope with extreme heat.



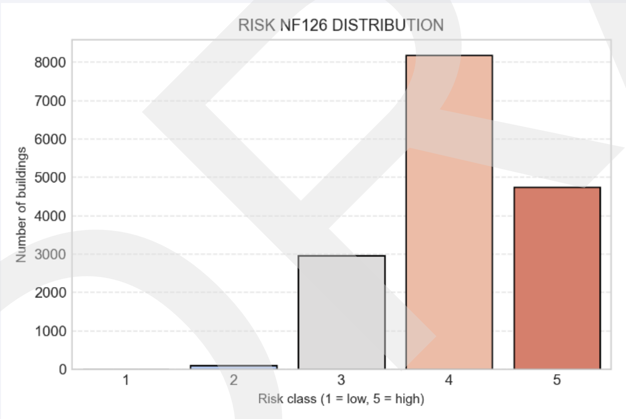
Risk assessment on BUILDINGS - Historical period

Analysis of heatwave risk in Syros buildings, for the historical period, shows that 62.1% (about 13,900 of 22,700) are categorized as high-risk classes 4–5, with 31.3% in the highest class 5. The risk map highlights high-risk buildings (red/orange) mainly around Hermoupolis city center, while low-risk buildings (green/blue) are mostly in peripheral zones. This spatial distribution stems from the modeling method, which assigns 72% of central buildings post-1920 construction dates (indicating higher vulnerability scores of 3–4) combined with higher historical temperatures (>32.5°C, score 4–5). The risk, calculated as vulnerability × temperature score, peaks where urban density and recent construction overlap, illustrating a realistic urban heat island effect.

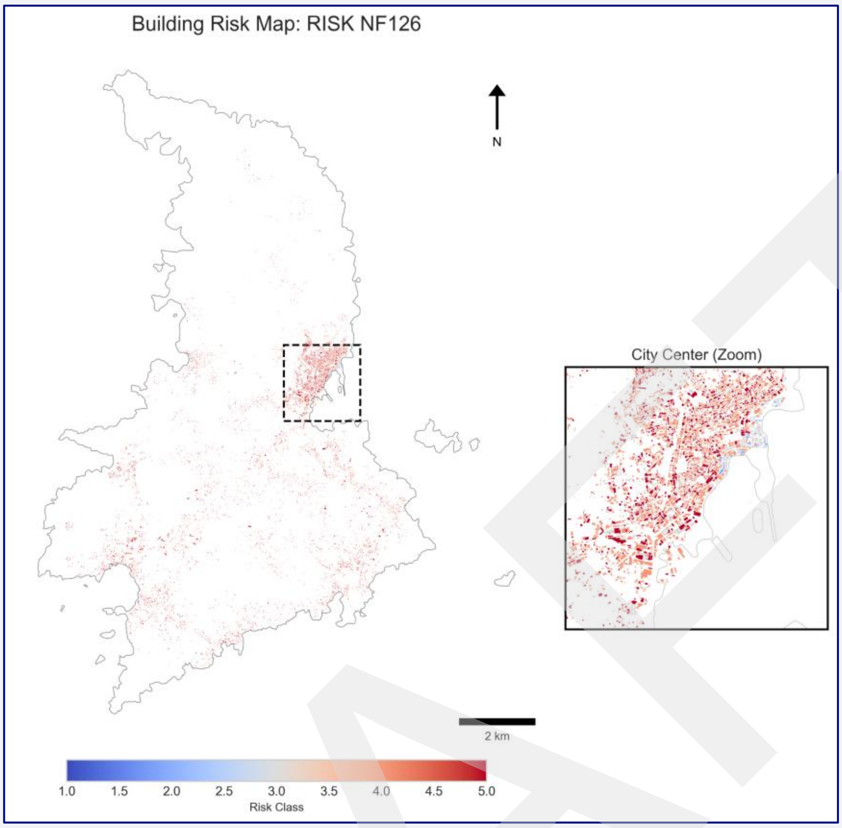




Risk assessment on BUILDINGS - SSP126 Near Future

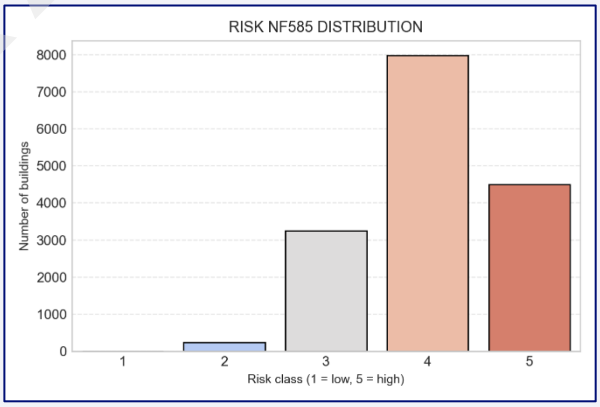


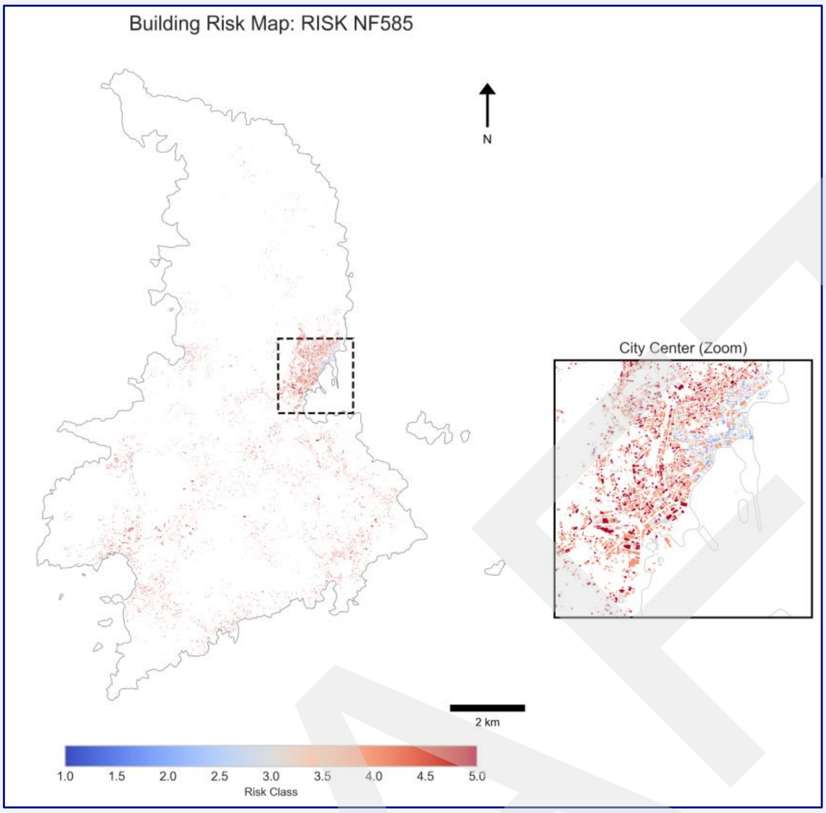
The near-future SSP1-2.6 scenario shows 65.0% of buildings (about 14,300 out of 22,000) fall into high-risk categories 4–5, with 32.3% in the highest category 5. The risk distribution closely mirrors historical data (62.1% high risk), indicating little change under this low-emissions pathway. The spatial pattern shows a strong concentration of high-risk buildings (red/orange) around Hermoupolis center, while low-risk areas (green/blue) dominate the outskirts. This consistency suggests vulnerability, mainly due to construction age, plays a larger role than the near-future temperature increase (nf45), which isn't enough to push many buildings across risk levels under SSP1-2.6. The urban core continues to be the main focus for interventions, with no major expansion of risk into surrounding areas.



Risk assessment on BUILDINGS - SSP585 Near Future

The near-future SSP5-8.5 (risk_nf585) scenario indicates that 65.0% of buildings—approximately 14,300 out of 22,000—are classified as high-risk levels 4–5, with 32.3% falling into class 5. This distribution closely resembles the patterns observed in historical data and SSP1-2.6, showing little change in risk class frequencies. The spatial map confirms that high-risk buildings (depicted in red and orange) are mainly concentrated around Hermoupolis center, maintaining the urban core as a vulnerability hotspot. Under the high-emissions SSP5-8.5 scenario, this suggests that the vulnerability score, primarily construction age, influences risk more than temperature projections. Even with the worst-case warming, the near-term nf85 temperature rise is not sufficient to push enough buildings into higher risk categories to significantly change the overall distribution.





7.2 Multi-hazard risk assessment

The multi-hazard risk assessment on Rhodes Trial is based on the combined risk of Wildfires, Extreme winds, and Heatwaves. The multi-hazard indicator used for the risk assessment analysis is based on the total number of days, in the 25year period when for each grid cell:

1) FWI > 80
2) Max temperature > 30oC
3) Wind > 10.8 m/s

7.2.1 Multi-hazard risk for economy

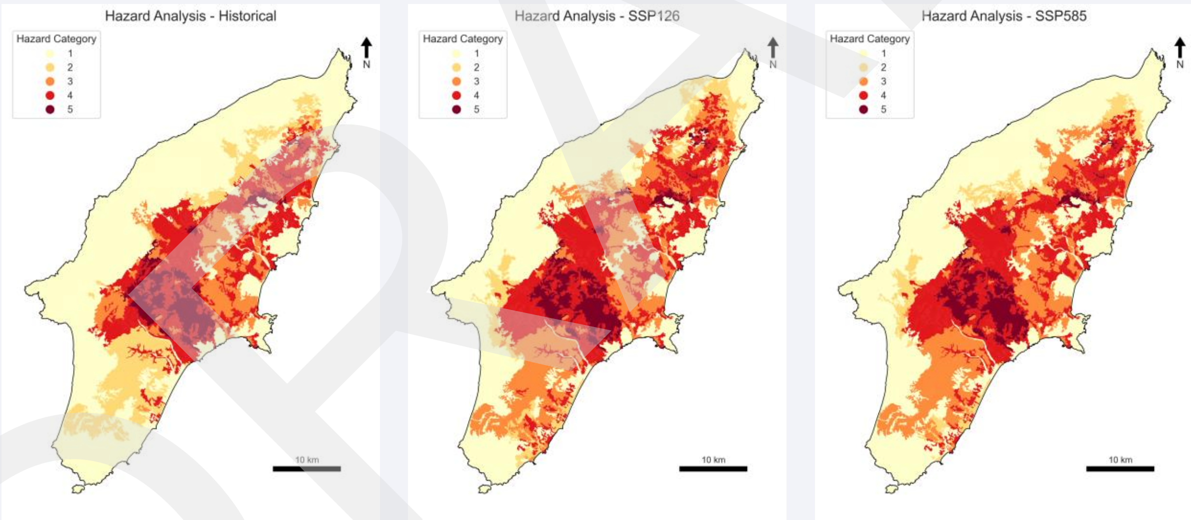
Multi-hazard risk assessment of ECONOMIC ASSETS

Risk assessment methodology

This assessment's goal is evaluating the potential economic damages to properties on the island of Rhodes. As presented above, Section 4.2.3, risk framework combines hazard, exposure, and vulnerability components to estimate the wildfire risk of the economics assets of the trial area. The assessment was done for multi-hazard scenarios to see the evolution of the wildfire risk between them.

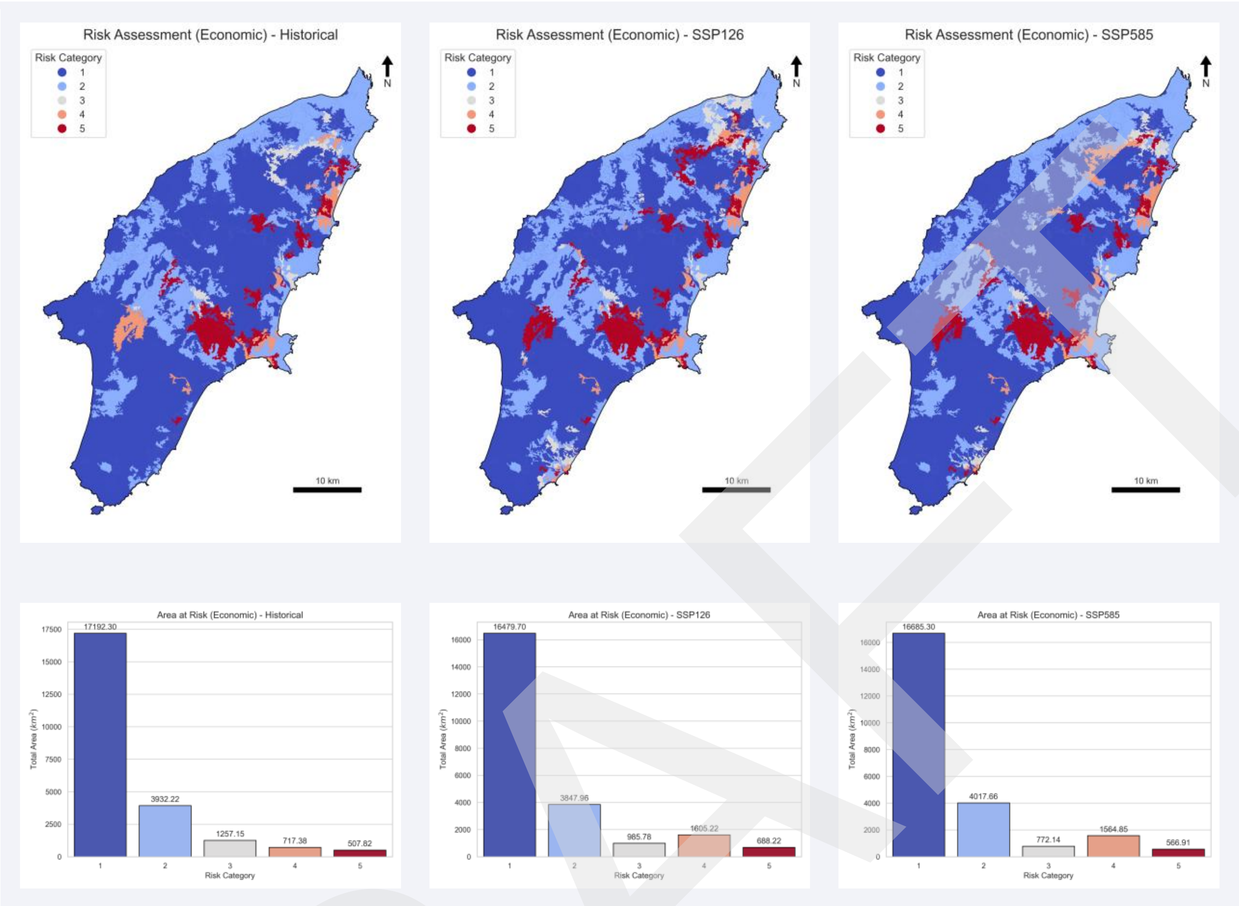
Hazard assessment of ECONOMIC ASSETS

The multi-hazard assessment is based on the multi-hazard's indicator on the island of Rhodes. As shown in the left figure, the wildfire hazard is increasing in the future scenarios, in comparison with the historical data, mainly in the near future period. As expected, the multi-Hazard is more profound in the center section of the island (historically affected by wildfires). The relatively small extend of the high-risk areas (> 3) is due to the small density (i.e., small reparation cost) number of economic assets in that area.



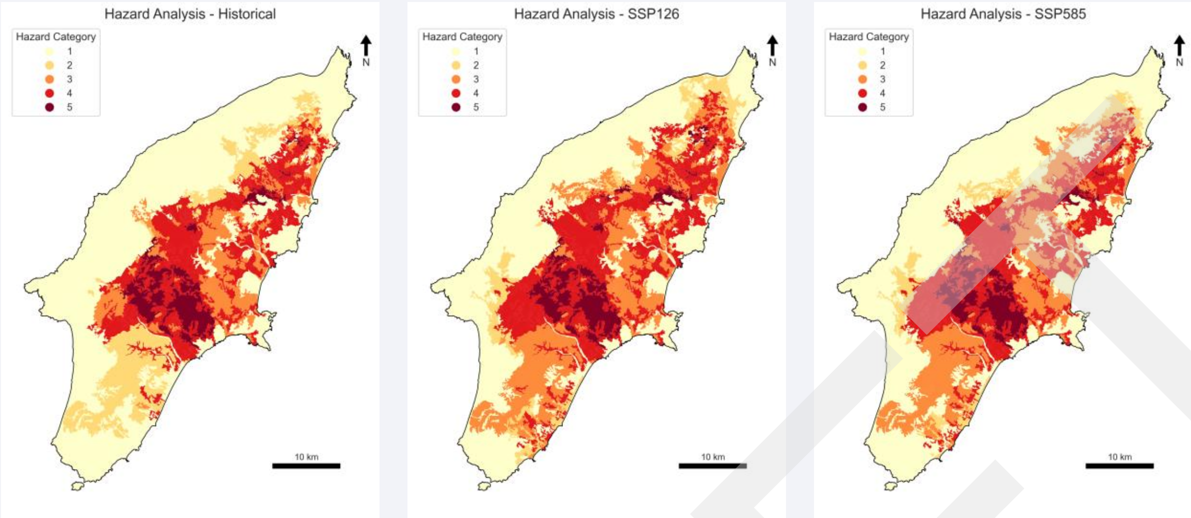
Multi hazard risk assessment of ECONOMIC ASSETS

The vulnerability of the various assets remains the same regardless of the hazard. This is based on the assumption that the compound effect, as expressed by these indicators will have the same effect on the economic assets as a wildfire event, which given the climatic conditions will have higher chances to take place. As shown in the hazard maps for the historical period and the future scenarios, the high-risk areas are located in all cases in the central-east part of the island. The areas overlap with all the historical wildfires affected sectors of the island. There is a slight increase in multi-hazard risk in the SSP126 near future scenario on the northern and eastern part of the island. The increase in multi-hazard risk is milder for the SSP585 scenario, for the same period.



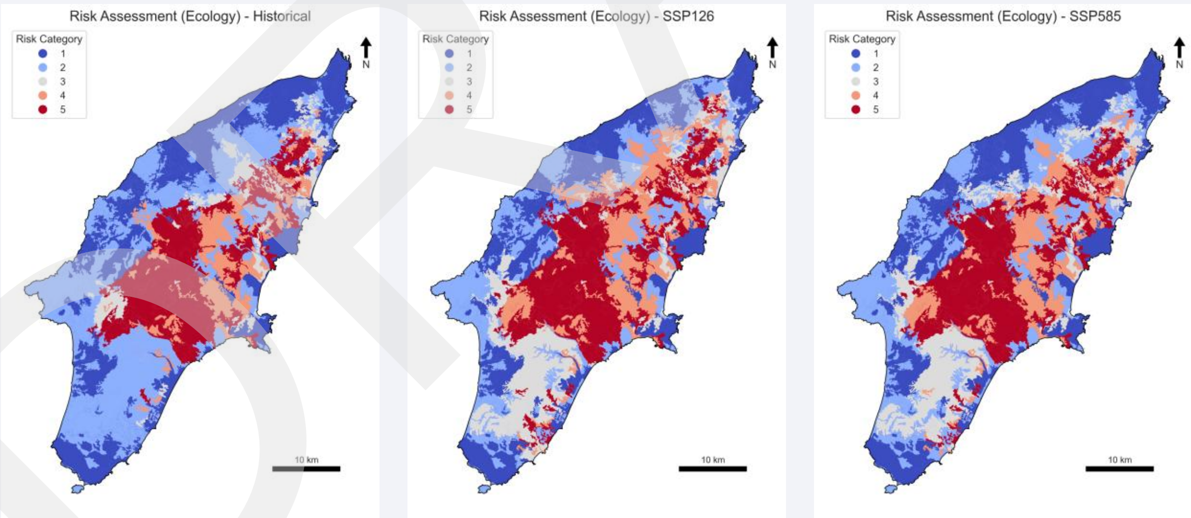
7.2.2 Multi-hazard risk for ecology

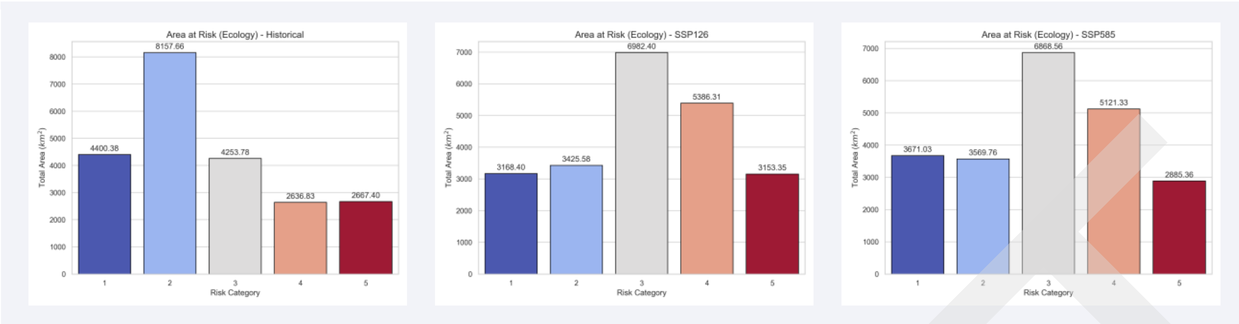
Multi-hazard risk assessment of ECOLOGY
Multi hazard risk assessment methodology
This assessment's goal is evaluating the potential economic damages to properties on the island of Rhodes. As presented above, Section 4.2.3, risk framework combines hazard, exposure, and vulnerability components to estimate the wildfire risk of the ecology of the trial area. The assessment was done for multi-hazard scenarios to see the evolution of the wildfire risk between them.
Hazard assessment on ECOLOGY
The wildfire hazard is based on the multi-hazard's indicator on the island of Rhodes. As shown in the left figure, the wildfire hazard is increasing in the future scenarios, in comparison with the historical data.



Multi hazard risk assessment on ECOLOGY

The multi-hazard risk assessment on the ecology of the Trial area indicates a high-risk region (> 3) in the center of the island and along the mountain ridge of the island which spans from the south-western peninsula to the north-east part of the island 10 km from the city of Rhodes. This observation can be made for both historical and future scenarios. There is an increase in multi-hazard risk in the SSP126 scenario in the central part of the island. The SSP585 scenario risk assessment shows less high-risk areas, but still more than the historical period. The change in multi-hazard risk is also evident in the bar charts for each scenario. There is a clear shift towards higher risk categories, with minor differences between the 2 future scenarios.





7.2.3 Multi-hazard risk for people

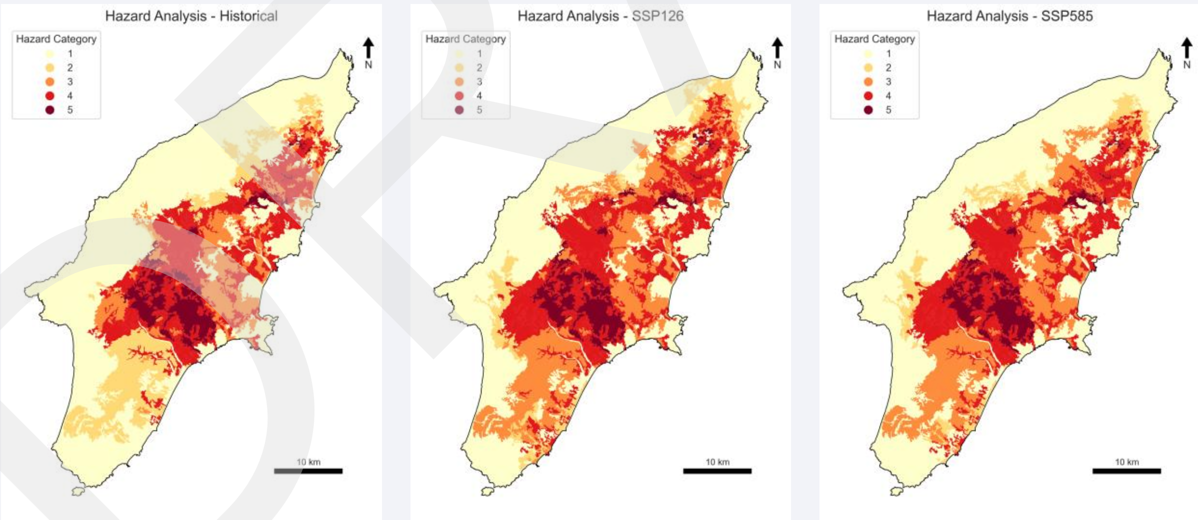
Multi-hazard risk assessment on PEOPLE

Risk assessment methodology

As presented above, Section 4.2.3, risk framework combines hazard and vulnerability components to estimate the wildfire risk of the population. The assessment was done for different scenarios to see the evolution of the wildfire risk between them.

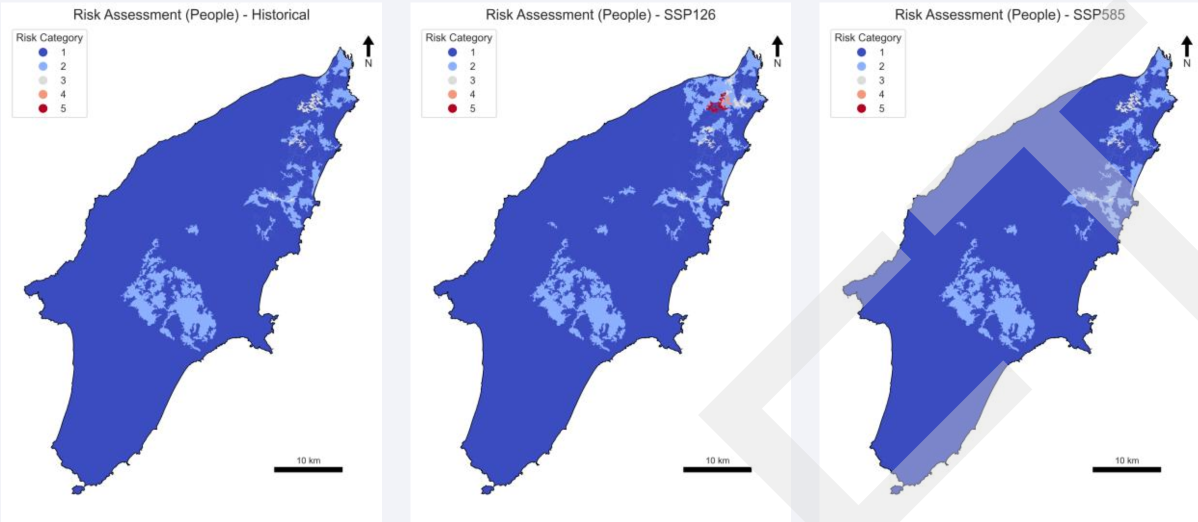
Hazard and Exposure assessment on PEOPLE

The wildfire hazard is based in the multi-hazards' indicator on the island of Rhodes. As shown in the left figure, the wildfire hazard is increasing in the future scenarios, in comparison with the historical data.

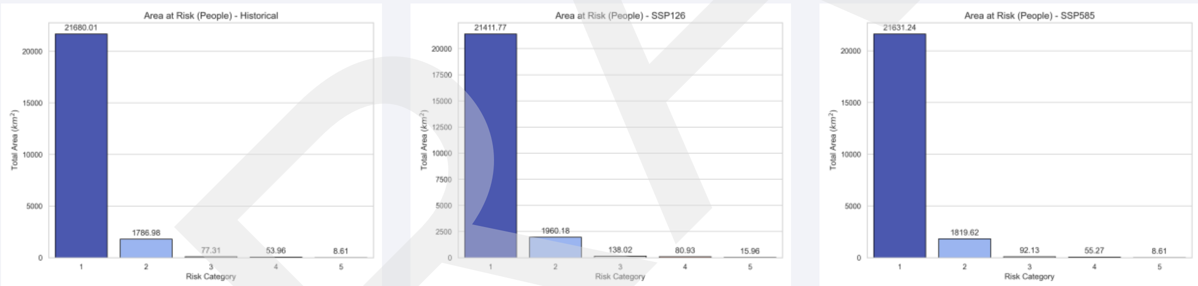


Multi hazard risk assessment on PEOPLE

The multi-hazard risk assessment on the population is relatively low in most parts of the island (< 2). The only significant risk on the population is identified for the SSP126 scenario on the outskirts of the city of Rhodes. This is due to the peri-urban characteristics of the area in addition to an elevated population density, in comparison with other areas.



Graphical representation of the multi-hazard risk assessment results shows no significant change in the risk on the local population, except in a small area to the northern part of the island, close to the city of Rhodes.



7.3 Adaptation scenario risk assessment

7.3.1 Adaptation scenario for risk reduction in ecology against wildfires and multi-hazard events

Based on the proposal by the local stakeholders and the local authorities, there is an initiative in replacing the Pines trees with Ceratonia siliqua in an attempt to reduce wildfire vulnerability, as well as increasing the local agricultural economy by exploiting the products of these trees. The change in flammability prior and after the adaptation scenario is presented in figure below.

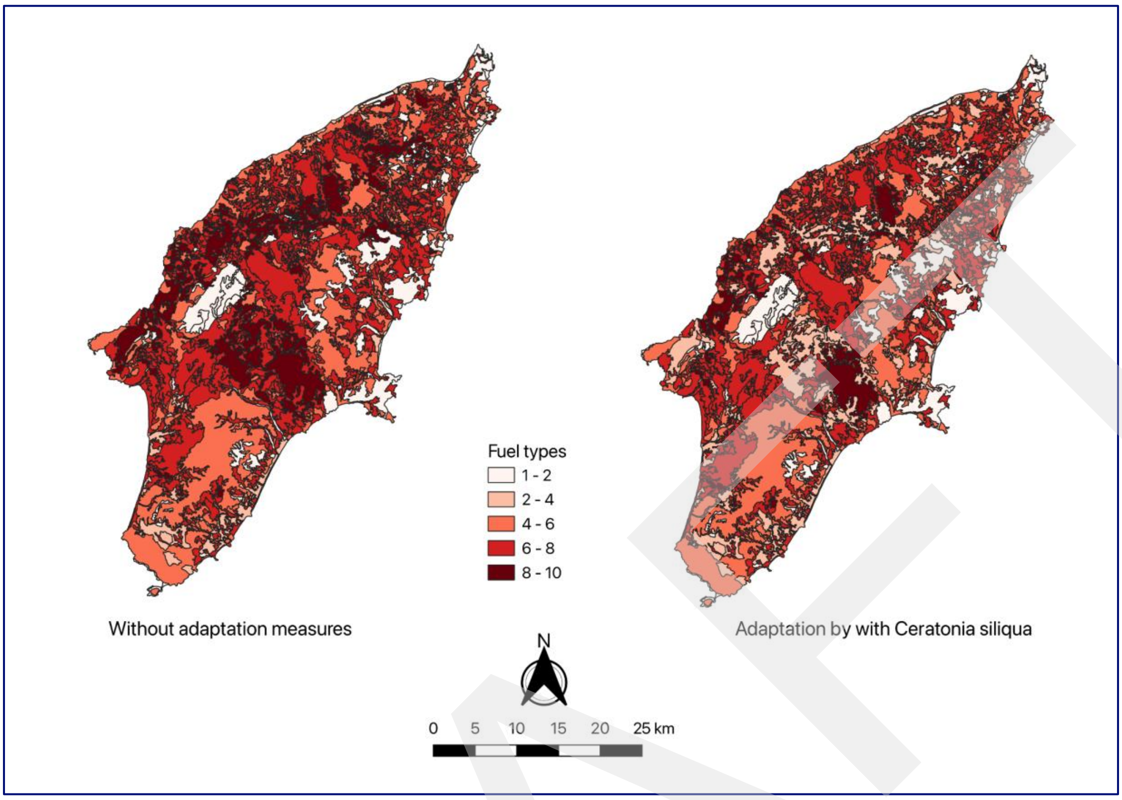
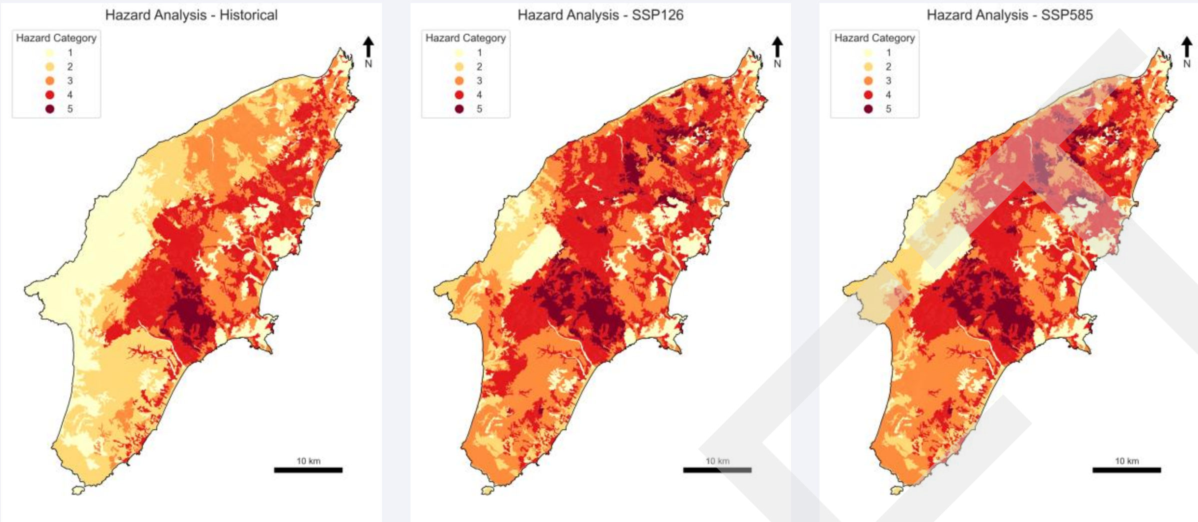


Figure 42. Single and multi hazard scenarios

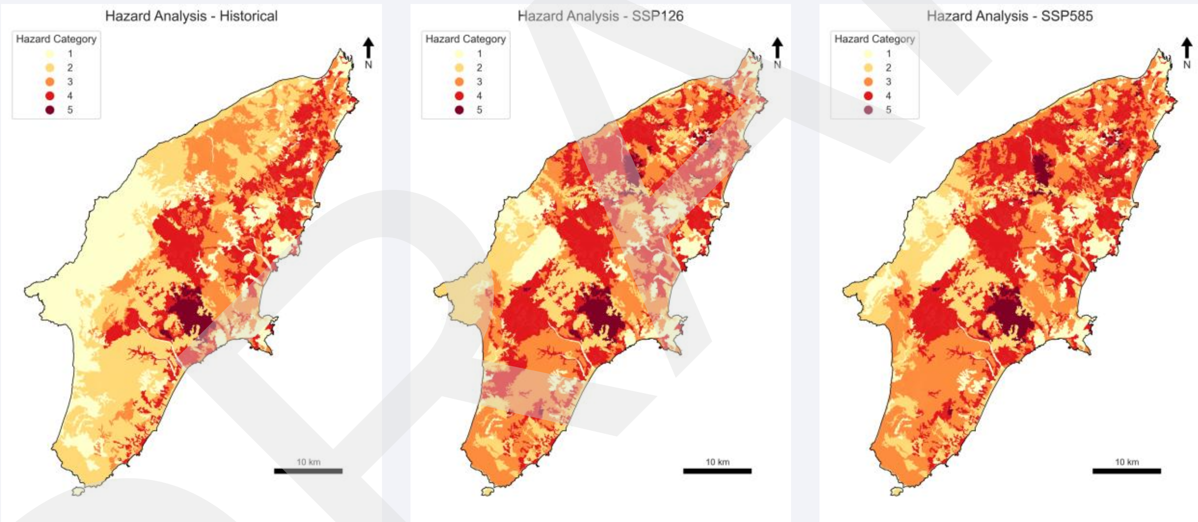
By replacing the vegetarian in key and previously damaged areas the wildfire risk is reduced in both single (Figure 42) and multihazard scenarios (Figure 42). In the case of Ecology, the risk reduction is dramatic. The risk reduction is sufficient in both historical and future scenarios and remains constant regardless of it.

WILDFIRE with adaptation risk assessment on ECOLOGY
Risk assessment methodology
As presented above, Section 4.2.3, risk framework combines hazard and vulnerability components to estimate the wildfire with adaptation risk of the ecology. The assessment was done for different scenarios to see the evolution of the multi-hazard risk between them.
Wildfire assessment on ECOLOGY
The wildfire hazard is based on the hazard indicator on the island of Rhodes. As shown in the figures, the wildfire hazard is increasing in the future scenarios, in comparison with the historical data. Minor differences can be observed between the two future scenarios.

Hazard analysis without adaptation solutions



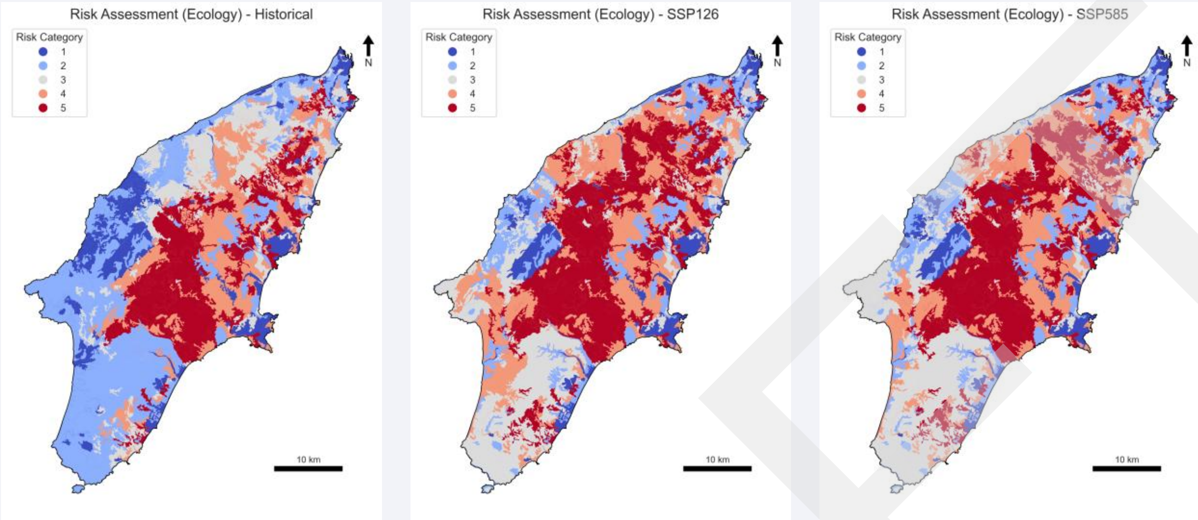
Hazard analysis with adaptation solution



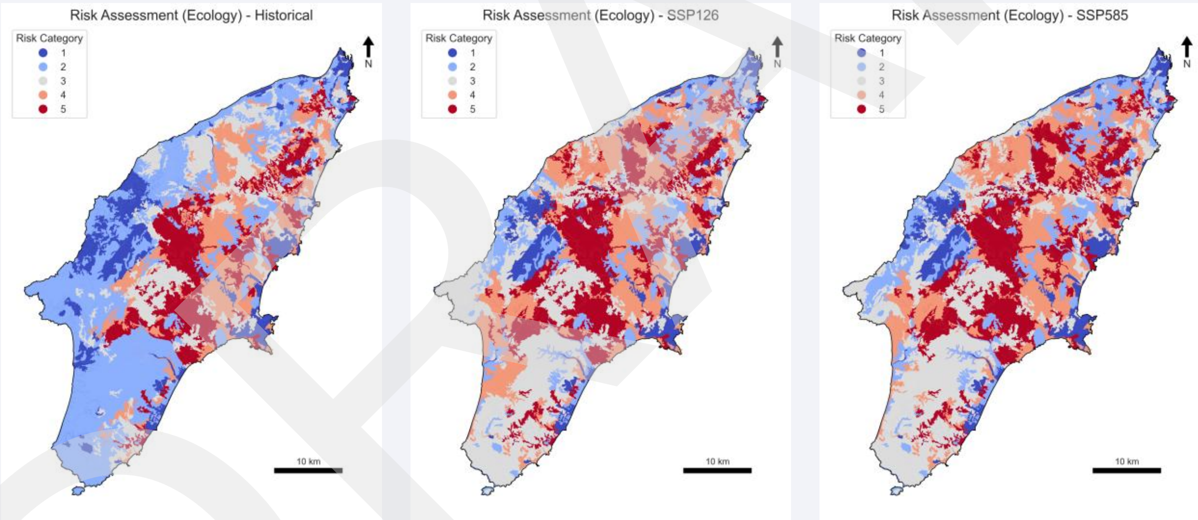
The replacement of the existing vegetation with Ceratonia siliqua decreases the wildfire hazard significantly in the fire prone areas of the island. The implementation of such adaptation solution is difficult to implement given the extent of Trial area, but systematic adaptation with a long-term planning will increase the wildfire resilience of the island.

Wildfire risk assessment on ECOLOGY

Risk assessment without adaptation solutions

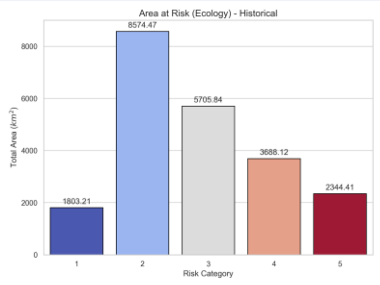


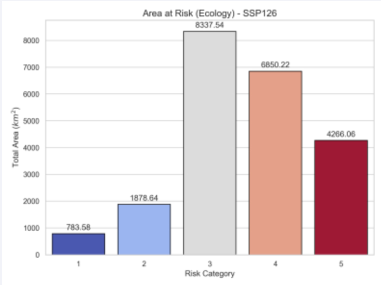
Risk assessment with adaptation solution

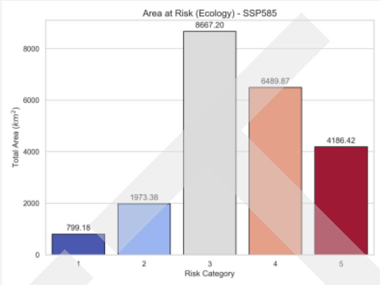


The comparison of the risk assessment shows the reduction in wildfire risk on Rhodes Island. Especially, category 5 risk areas are decreased by nearly 32% in all scenarios. On the contrary, the category 2 risk areas are increasing, as expected by the reintroduction of the less flammable species in the local fauna. Category 3 and 4 areas remain constant with minor changes.

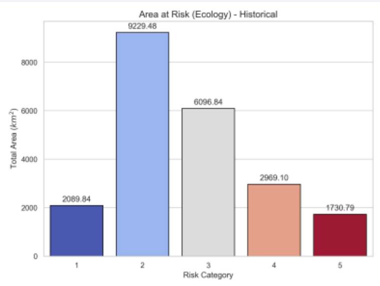
Risk assessment without adaptation solutions

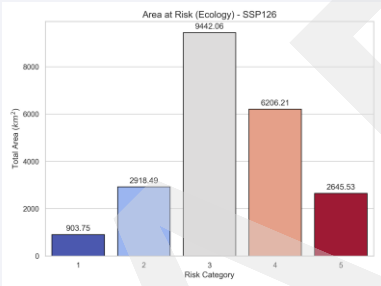


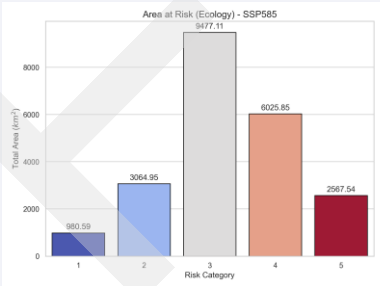




Risk assessment with adaptation solutions







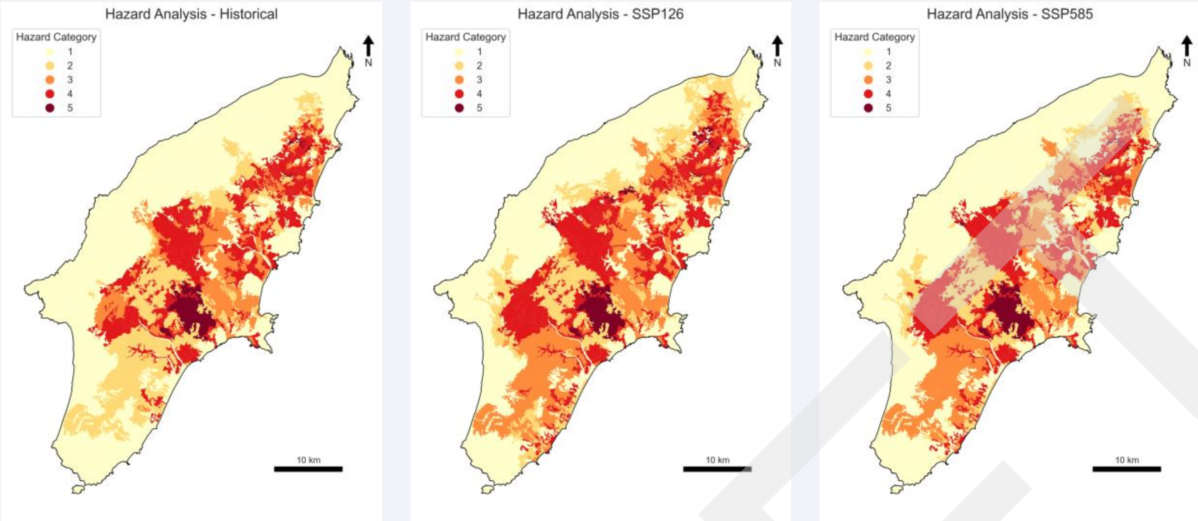
Multi-hazard adaptation risk assessment on ECOLOGY

Risk assessment methodology

As presented above, Section 4.2.3, risk framework combines hazard and vulnerability components to estimate the multi-hazard with adaptation risk of the ecology. The assessment was done for different scenarios to see the evolution of the multi-hazard risk between them.

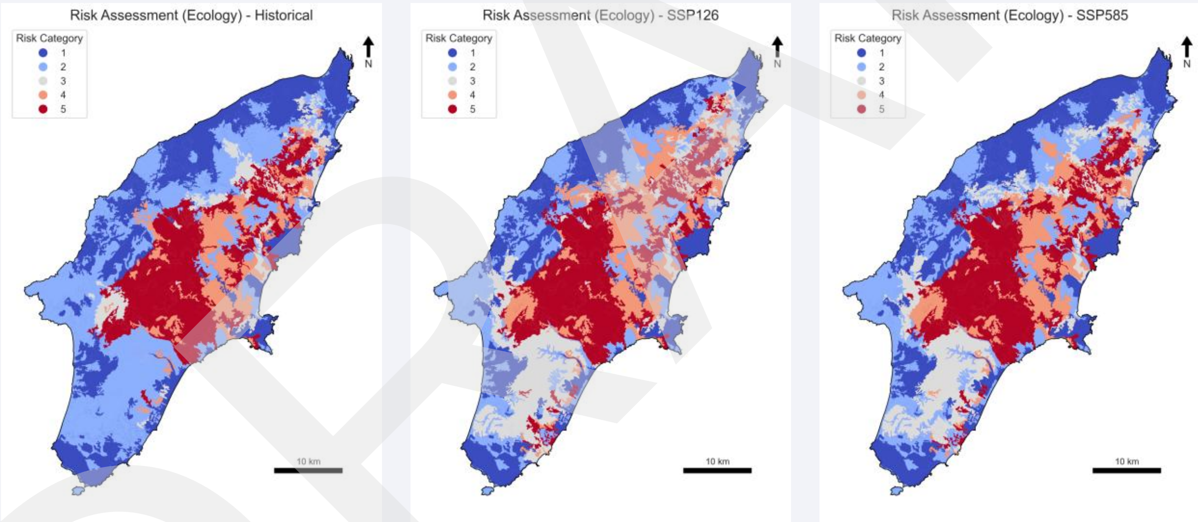
Multi-hazard assessment on ECOLOGY

The wildfire hazard is based on the multi-hazard's indicator on the island of Rhodes. As shown in the left figure, the wildfire hazard is increasing in the future scenarios, in comparison with the historical data.

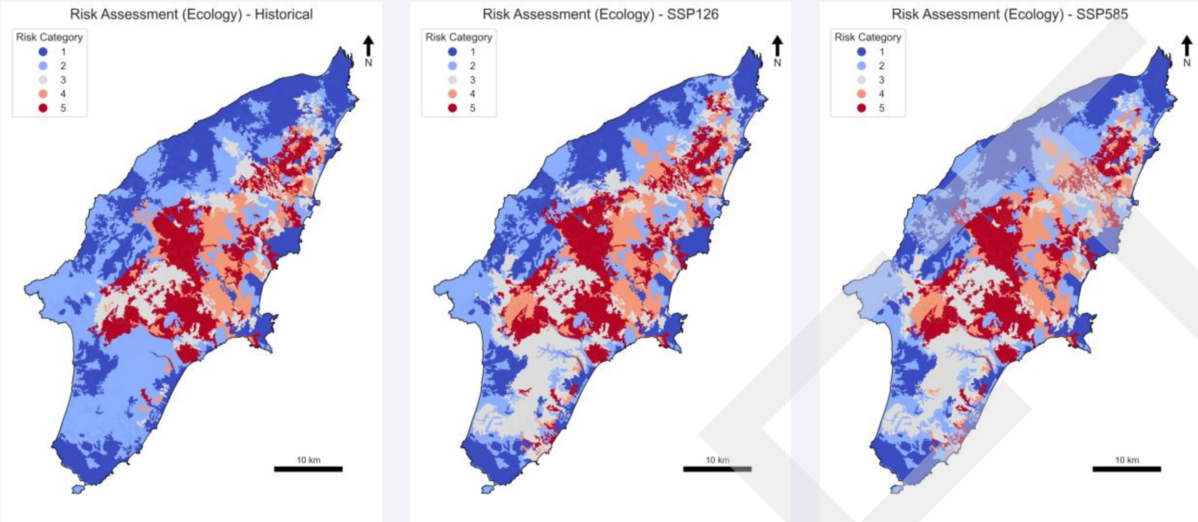


Multi hazard risk assessment on ECOLOGY

Risk assessment without adaptation solutions

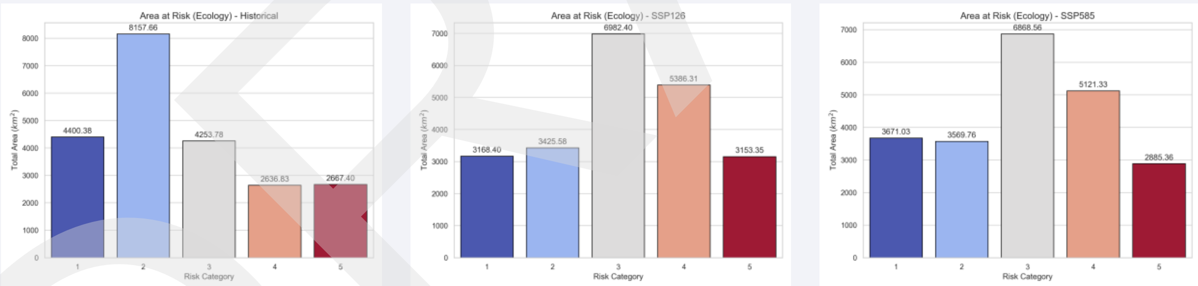


Risk assessment with adaptation solutions

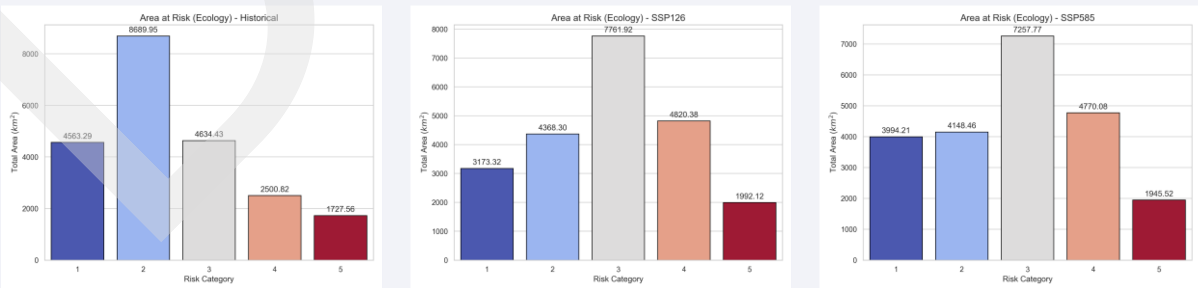


The comparison of the risk assessment shows the reduction in wildfire risk on Rhodes Island. Especially, category 5 risk areas are decreased by nearly 30% in all scenarios. A significant decrease can be observed in category 4 risk areas of around 10%. The areas with risk categories 3 and 2 remain relatively constant, with a minor increase in category 2 for the SSP126 scenario due to the decrease in category 1 areas.

Risk assessment without adaptation solutions



Risk assessment with adaptation solutions



7.3.2 Adaptation scenario for risk reduction in economic assets against wildfires and multi-hazard events

Based on the proposal by the local stakeholders and the local authorities, there is an initiative in replacing the Pines trees with Ceratonia siliqua in an attempt to reduce wildfire vulnerability, as well as increasing the local agricultural economy by exploiting the products of these trees. The change in flammability prior and after the adaptation scenario is presented in Figure below.

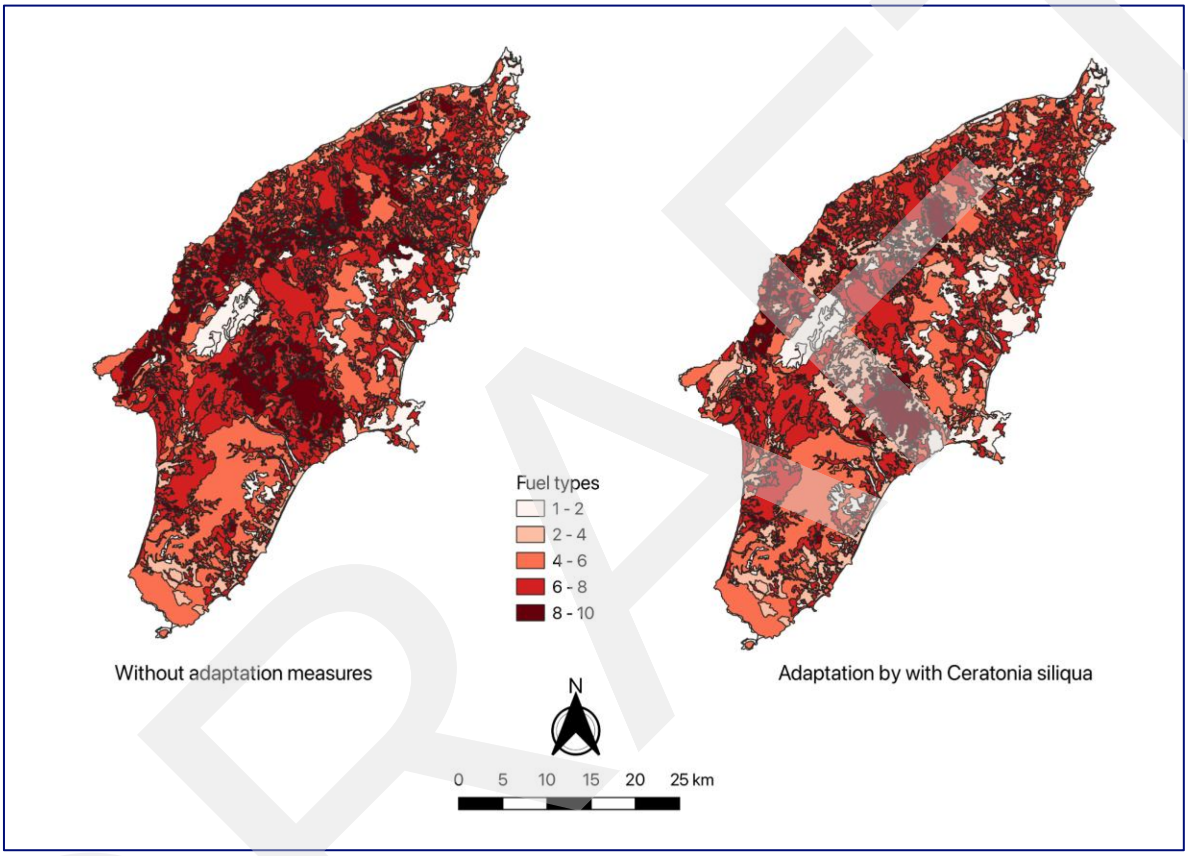


Figure 43. Adaptation scenario comparison

By replacing the vegetarian in key areas, the wildfire risk is reduced in both single (Figure above) and multihazard scenarios (Figure above). In the case of Ecology, the risk reduction is dramatic. The risk reduction is sufficient in both historical and future scenarios and remains constant regardless of it.

Wildfire with adaptation risk assessment on ECONOMIC ASSETS

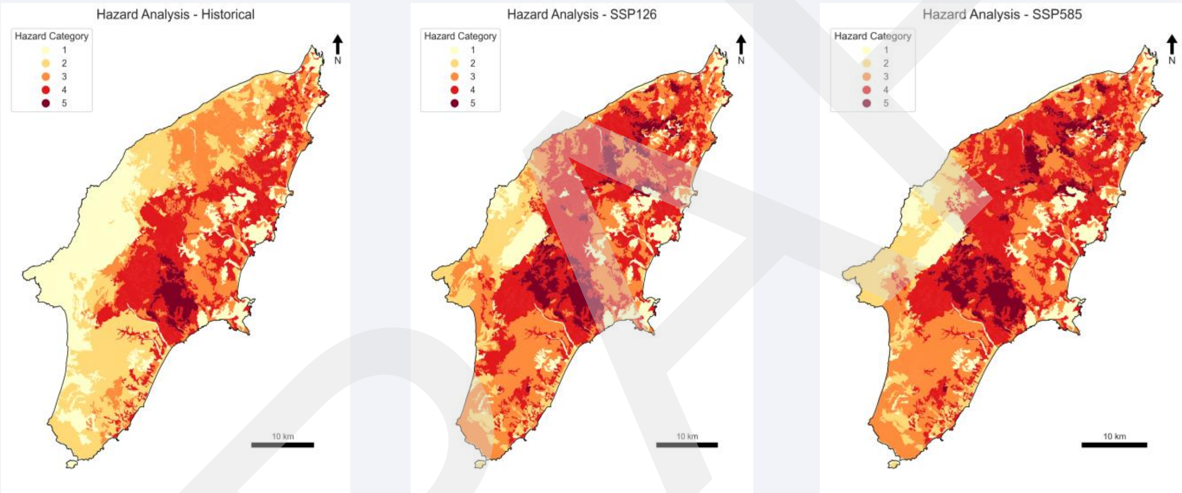
Risk assessment methodology

As presented above, Section 4.2.3, risk framework combines hazard and vulnerability components to estimate the wildfire with adaptation risk of the ecology. The assessment was done for different scenarios to see the evolution of the multi-hazard risk between them.

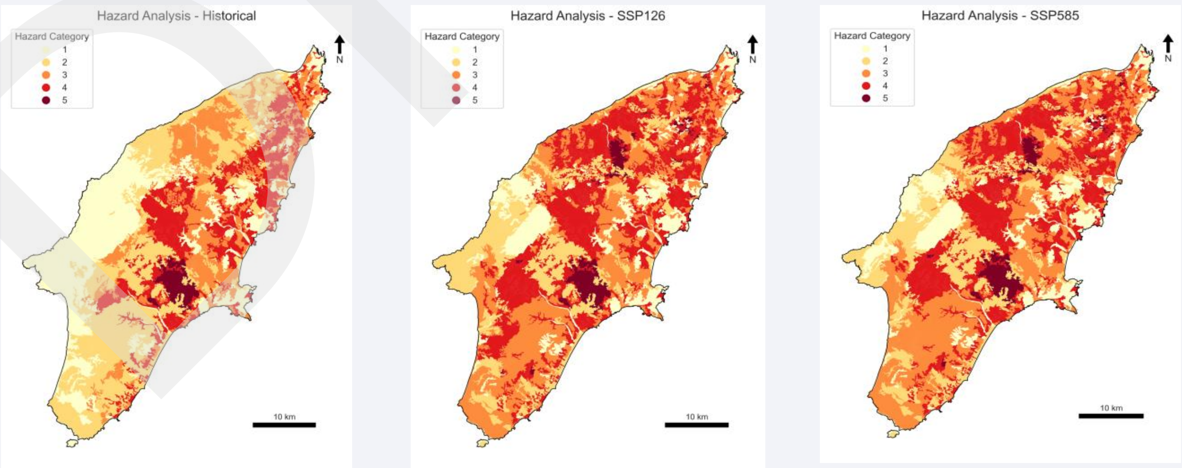
Wildfire assessment on ECONOMIC ASSETS

The wildfire hazard is based on the hazard indicator on the island of Rhodes. As shown in the Figures, the wildfire hazard is increasing in the future scenarios, in comparison with the historical data. Minor differences can be observed between the two future scenarios.

Hazard analysis without adaptation solutions



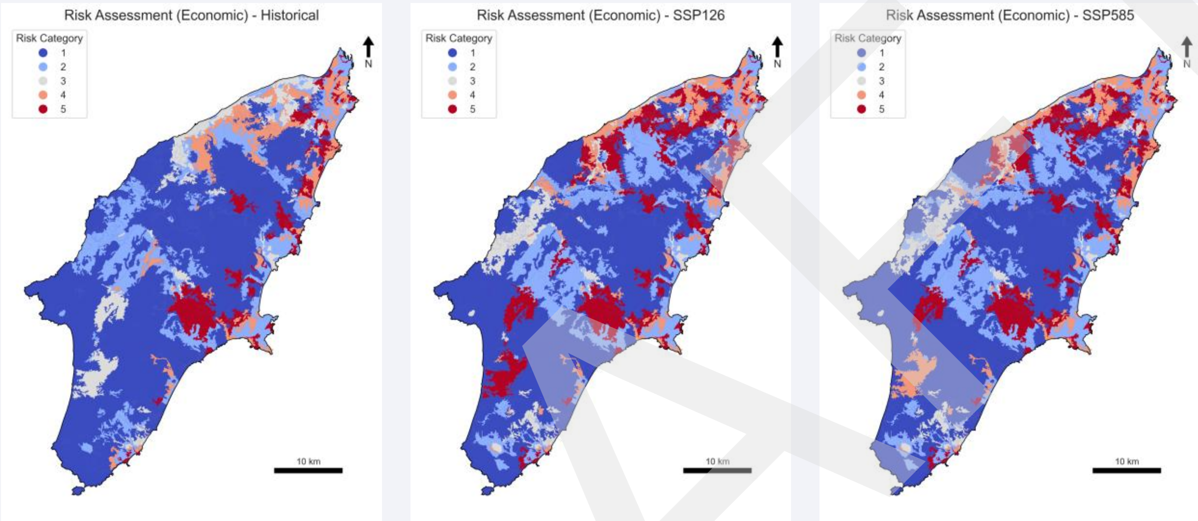
Hazard analysis with adaptation solution



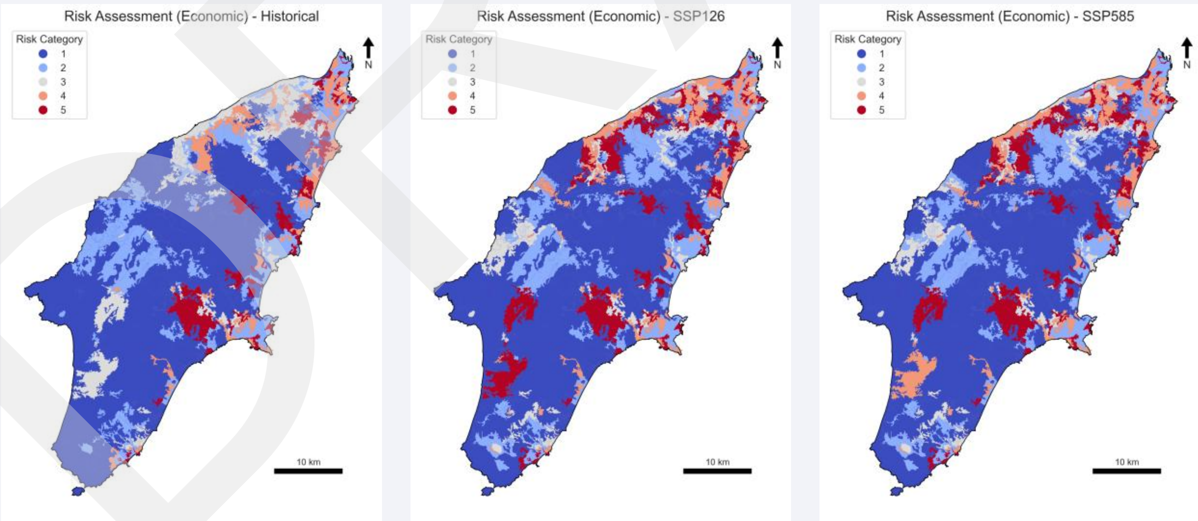
The replacement of the existing vegetation with Ceratonia siliqua decreases the wildfire hazard significantly in the fire prone areas of the island. The implementation of such adaptation solution is difficult to implement given the extent of Trial area, but systematic adaptation with a long-term planning will increase the wildfire resilience of the island.

Wildfire risk assessment on ECONOMIC ASSETS

Risk assessment without adaptation solutions

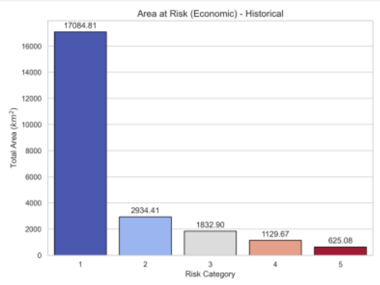


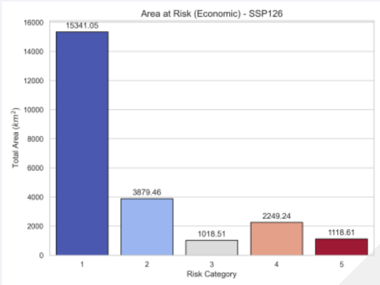
Risk assessment with adaptation solution

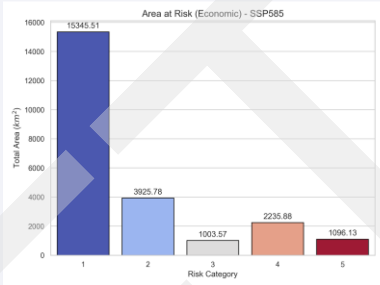


The comparison of the risk assessment shows the reduction in wildfire risk on Rhodes Island. Especially, category 5 and 4 risk areas are decreased by nearly 20% in all scenarios. On the contrary, the category 3 risk areas are increasing by 10%, as expected by the reintroduction of the less flammable species in the local fauna. Category 1 and 2 areas show minor increases.

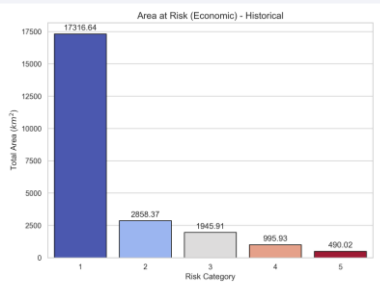
Risk assessment without adaptation solutions

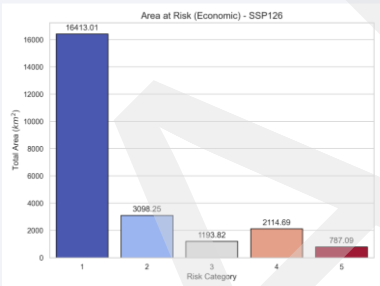


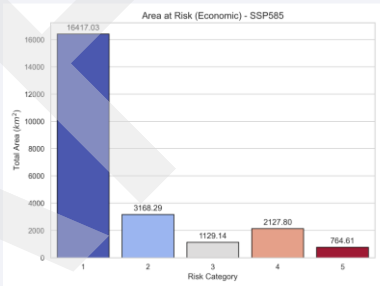




Risk assessment with adaptation solutions







Multi-hazard with adaptation risk assessment on ECONOMIC ASSETS

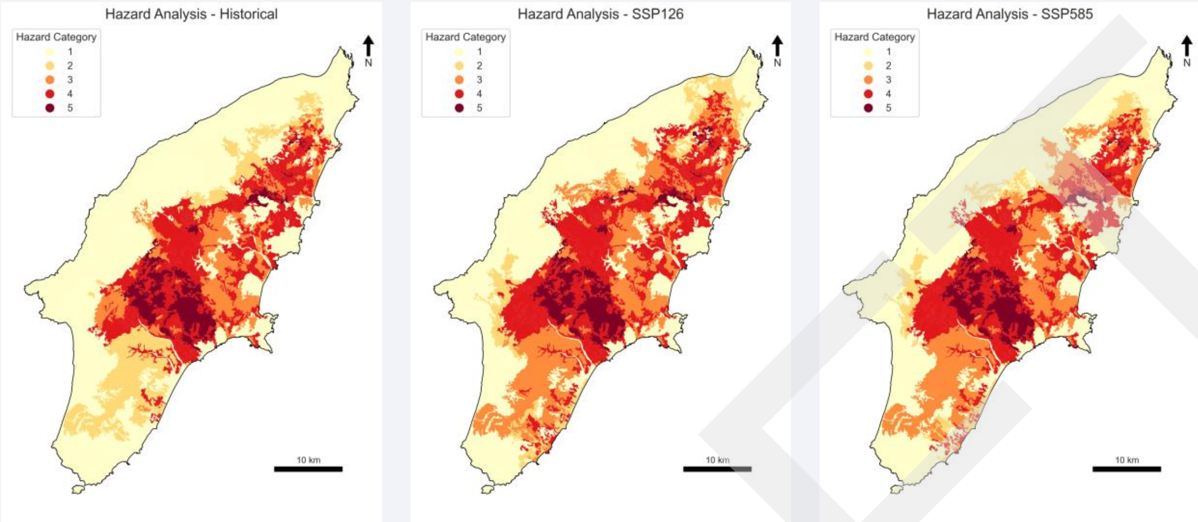
Risk assessment methodology

As presented above, Section 4.2.3, risk framework combines hazard and vulnerability components to estimate the wildfire with adaptation risk of the ecology. The assessment was done for different scenarios to see the evolution of the multi-hazard risk between them.

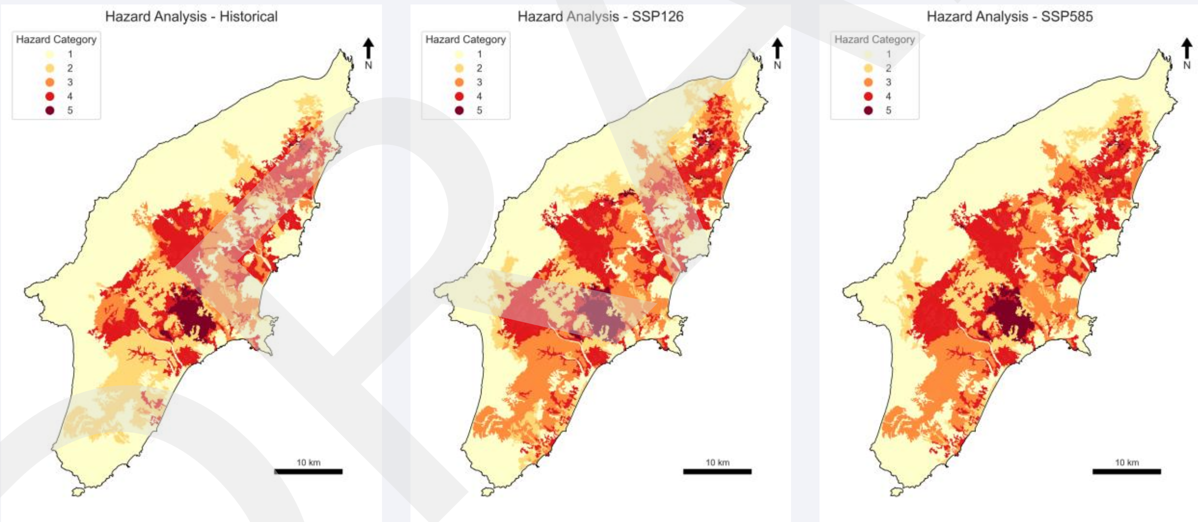
Multi-hazard assessment on ECONOMIC ASSETS

The wildfire hazard is based on the hazard indicator on the island of Rhodes. As shown in the figures, the wildfire hazard is increasing in the future scenarios, in comparison with the historical data. Minor differences can be observed between the two future scenarios.

Hazard analysis without adaptation solutions



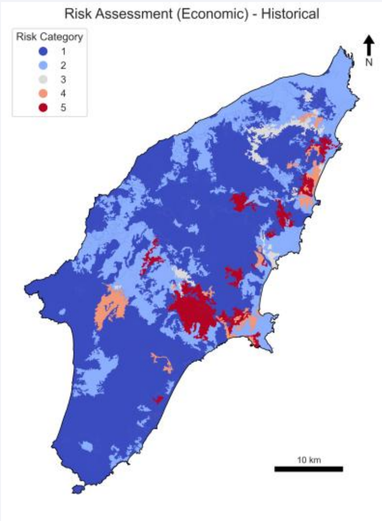
Hazard analysis with adaptation solution

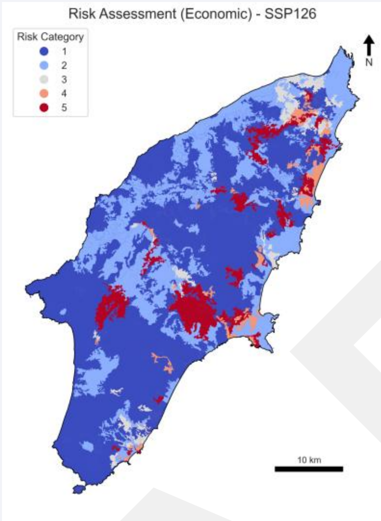


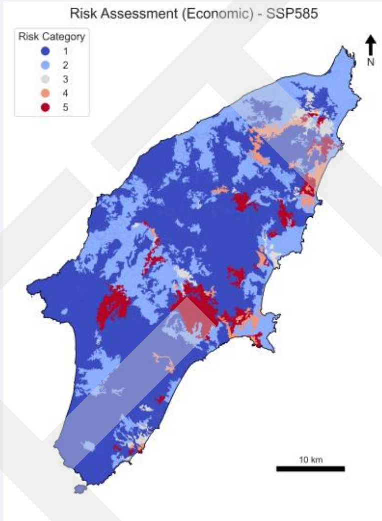
The replacement of the existing vegetation with Ceratonia siliqua decreases the multi-hazard significantly in the fire prone areas of the island. The implementation of such adaptation solution is difficult to implement given the extent of the Trial area, but systematic adaptation with a long-term planning will increase the wildfire resilience of the island.

Multi-hazard risk assessment on ECONOMIC ASSETS

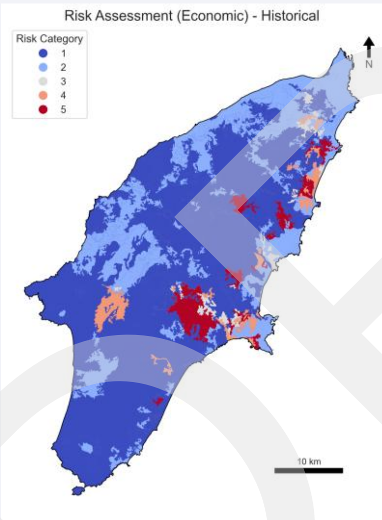
Risk assessment without adaptation solutions

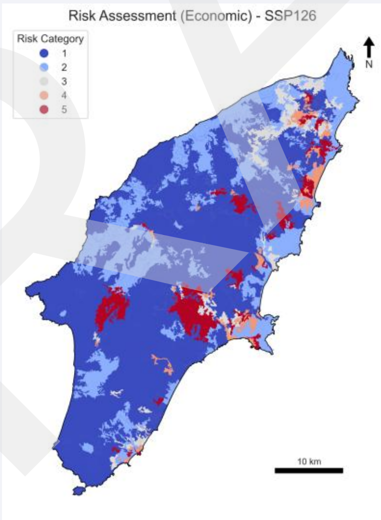


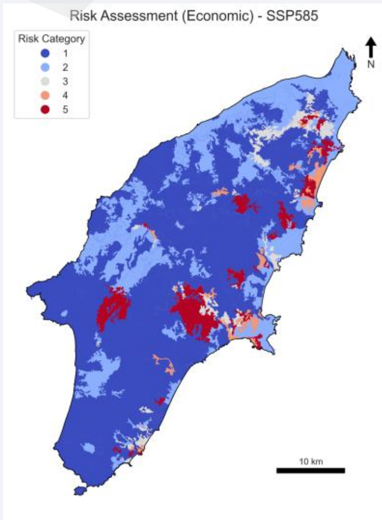




Risk assessment with adaptation solution

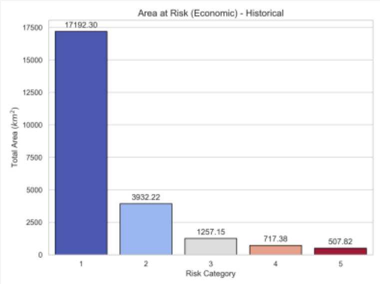


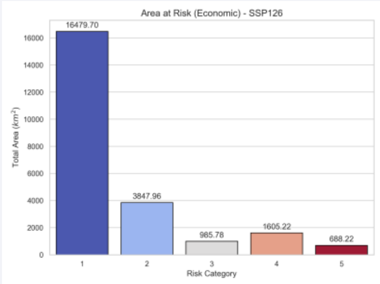


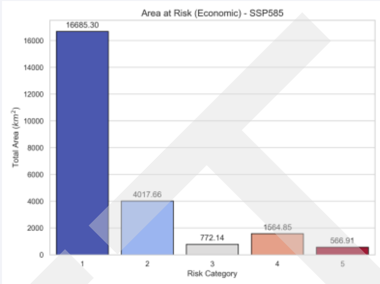


The comparison of the risk assessment shows the reduction in wildfire risk on Rhodes Island. Especially, category 5 risk areas are decreased by between 28 and 34% in all scenarios. On the contrary, the categories 1 and 3 risk areas are increasing, as expected by the reintroduction of the less flammable species in the local fauna, in the future scenarios. Categories 2 and 4 show minor negative changes.

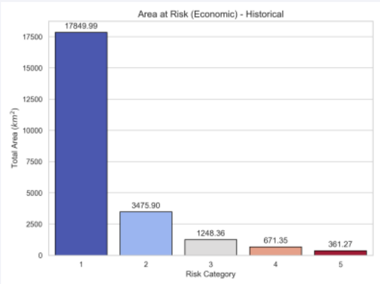
Risk assessment without adaptation solutions

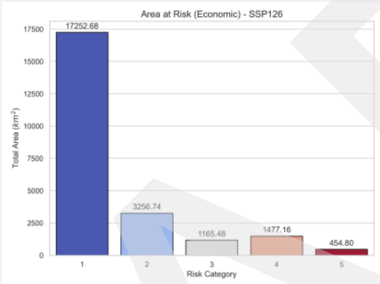


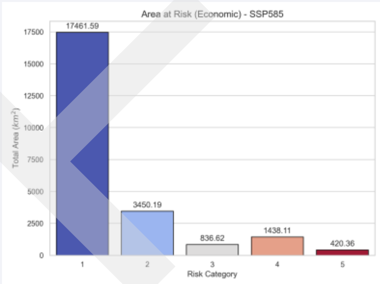




Risk assessment with adaptation solutions







7.3.3 Adaptation scenario for risk reduction in properties against heatwaves

The adaptation solution tested on the Trial Island of Syros, is retrofitting the properties for adaptation. The retrofitting will be implemented in buildings constructed between 1980 and 2010, which correspond to the properties with vulnerability score 2 and 3. The retrofitting is expected to drop their vulnerability by 1 class. Properties prior to 1980 are not taken into account, due to the different ant seismic construction code, thus built under different regulations. This means that any alteration on the buildings, might increase its earthquake vulnerability.

Heatwave with adaptation risk assessment on PROPERTIES

Risk assessment methodology

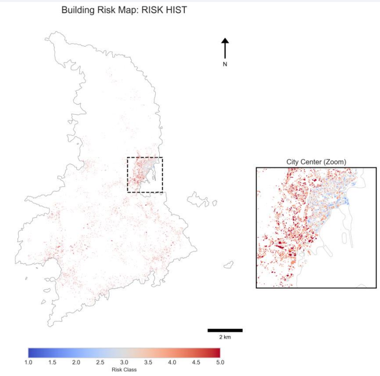
The risk assessment methodology used in the case of heatwaves on Buildings is presented in detail in Section 4.1.

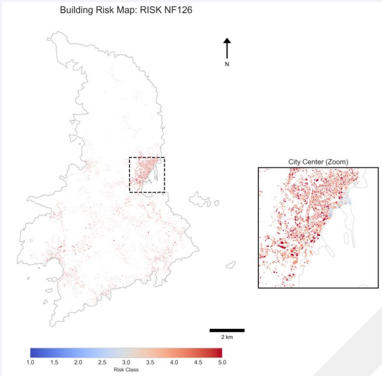
Hazard x Vulnerability = Risk

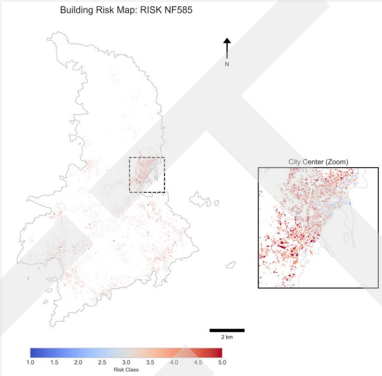
As hazard we use the R50 heatwave as it is translated to land surface temperature (LST) and as exposure and vulnerability information the construction period of the buildings and the construction regulations implemented at that period.

Heatwave risk assessment on PROPERTIES

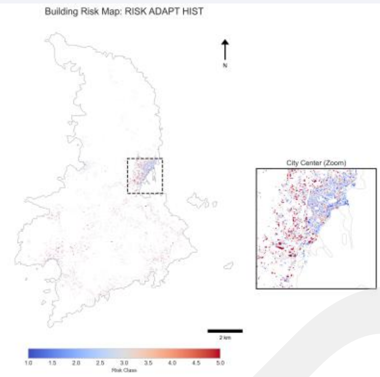
Risk assessment without adaptation solutions

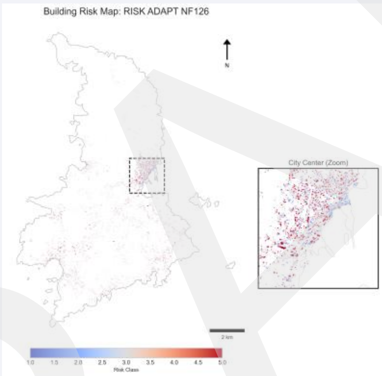


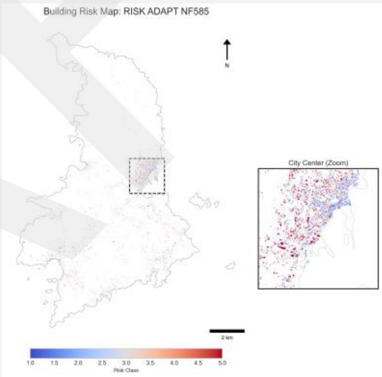




Risk assessment with adaptation solution

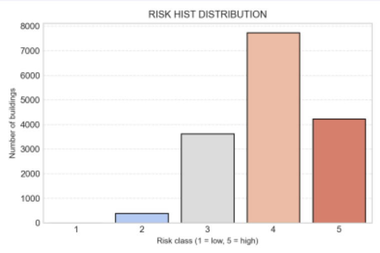


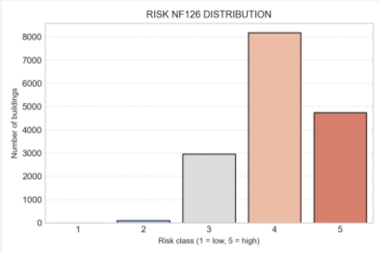


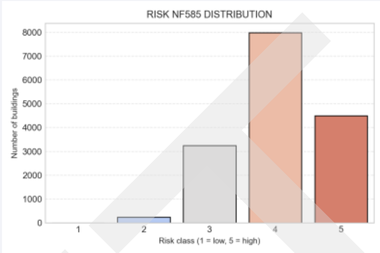


In the historical scenario (RISK HIST), most buildings are categorized within higher risk classes (4 and 5), with class 4 predominating. Following adaptation measures (RISK ADAPT HIST), the distribution shifts markedly towards lower and moderate classes (2 and 3), indicating a conspicuous overall reduction in building vulnerability. In the prospective scenario (RISK NF126), the majority of buildings continue to reside in high-risk categories (classes 4 and 5), signifying heightened vulnerability. Post-adaptation (RISK ADAPT NF126), there is a pronounced shift towards lower and moderate risk tiers (classes 2 and 3), illustrating the efficacy of adaptation strategies in mitigating building risk under anticipated future conditions. Under the high-emission scenario (RISK NF585), most buildings remain in high-risk categories (4 and 5), reflecting increased vulnerability due to more extreme environmental conditions. In the adaptation scenario (RISK ADAPT NF585), there is a noticeable redistribution towards lower and moderate risk classes (2 and 3), demonstrating that adaptive measures can substantially diminish building exposure even amidst severe future climate scenarios.

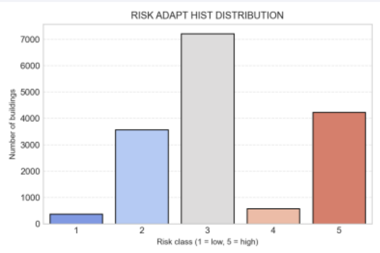
Risk assessment without adaptation solutions

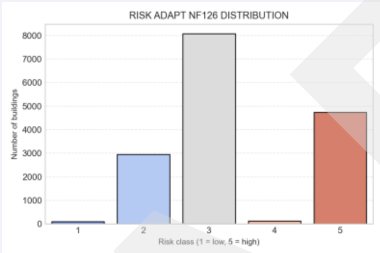


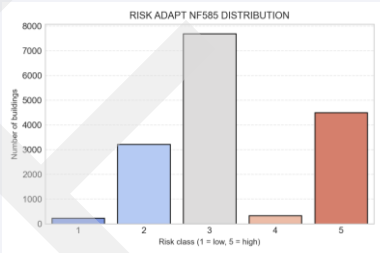




Risk assessment with adaptation solutions







8 Conclusions

ICARIA trials were designed as a part of the process leading to a final validation of the project results. As indicated in the sections 3 and 4, trialing includes far more than just the organization of the final trial events.

8.1 Resolving the research questions

At the end of the day, we need to understand what all the results gathered during the trial execution and discussed in previous sections actually mean in terms of research questions the consortium wanted to resolve. As indicated in section 3.3.2, ICARIA research questions were *not* designed as direct questions for the trial participants. In order to resolve them, ICARIA team has designed different data gathering methods, each with their own advantages and disadvantages. In the end, compromises had to be made to accommodate shorter than planned trial event duration and some of recommended data gathering activities were simplified or dropped altogether. Most notably, the number of planned interactive discussion sessions and interactive surveys during the trial events had to be drastically reduced and no interviews with key stakeholders were Organized. The level of achieved validation for each of the research questions is presented in Table 22 below.

Table 22. ICARIA research questions for the trials (as defined in ICARIA D4.1), and their mapped answers (below each question). The answers are based on methods described in Section 3.3.2) (e.g., participant feedback, questionnaires, etc.).

<table>
<tr><th>RQ No.</th><th>Research Question</th></tr>
<tr><td>RQ-Sci1</td><td>How plausible/reliable are ICARIA data/modelling results?</td></tr>
<tr><td colspan="2">ICARIA's data and modelling outputs and results seem reasonable within their defined scope and are generally perceived as potentially credible. However, reliability is limited by data dependency, limited multi-hazard and cascading risk treatment, and prototype maturity (as expected). Further validation, transparency, and increased TRL level (including more reliable data and accurate modelling) would be required for operational decision-making use.</td></tr>
<tr><td>RQ-Sci2</td><td>How easy/difficult/expensive would it be to apply the ICARIA solutions in new regions?</td></tr>
<tr><td colspan="2">Applying ICARIA solutions in new regions is technically feasible, not inherently costly, but context dependent. Core functions are intuitive and resilience components replicable. The barrier is data availability and preparation, needing technical expertise. Additional adaptation to local hazards and cascading risks may be needed, making implementation moderately demanding in data-poor contexts.</td></tr>
<tr><td>RQ-Sci3</td><td>Which data/modelling aspects of ICARIA solutions need to be further developed/improved?</td></tr>
<tr><td colspan="2">Key improvements should involve clearer data requirements and input guidance, enhanced modelling of multiple and cascading risks, broader hazard coverage, and better integration of verified datasets. Greater model transparency and adaptation of resilience indicators to different territorial contexts are also needed to strengthen trust and operational usability.</td></tr>
<tr><td>RQ-Sci4</td><td>To what extent does the functionality of the ICARIA tools go beyond the state of the art/ what is currently used in the region?</td></tr>
<tr><td colspan="2">The ICARIA tools go beyond current regional practice primarily in terms of integration, scenario analysis, and forward-looking risk modelling. The added value of combining hazard, exposure, vulnerability, and resilience assessments within a single, structured platform was recognized as innovative/useful. In particular, the ability to compare multiple climate and adaptation scenarios, visualize projections, and assess cascading and cross-sectoral impacts was seen as more advanced than commonly used approaches, which are often fragmented or static. However, usability and contextual limits mean it may not yet outperform existing tools.</td></tr>
</table>

<table>
<tr><th>RQ No.</th><th>Research Question</th></tr>
<tr><td>RQ-Ex1</td><td>How easy or difficult is it to use the solutions?</td></tr>
<tr><td colspan="2">The solutions were generally user friendly for use, with intuitive navigation and clear core functions such as scenario comparison and data upload. However, RAF and particularly RAT posed challenges, e.g., unclear terminology, missing options, limited context, and structural limits in addressing diverse assets and responsibilities, which required guidance from the developers/tool owners. Overall usability was positive, though advanced steps and data preparation demanded expert support.</td></tr>
<tr><td>RQ-Ex2</td><td>How easy or difficult is it to understand the results/recommendations offered by the solutions?</td></tr>
<tr><td colspan="2">ICARIA outputs were mostly understandable, with core workflows and scenario comparisons rated as clear or easy. Some elements, such as RAF/RAT charts, map functionalities, and multi-step workflows, required guidance or additional explanation. Participants could interpret recommendations, but comprehension was improved with support, and clearer documentation or non-expert-friendly instructions would enhance usability.</td></tr>
<tr><td>RQ-Ex3</td><td>What needs to be done to improve the user experience / usability of the solutions?</td></tr>
<tr><td colspan="2">Usability can be improved through clearer terminology, consistent response options (e.g., “not applicable”), and better contextual framing (crisis vs. normal operations). Simplified navigation, stronger orientation cues, and clearer sequencing across modules are needed. Enhanced, non-expert guidance for data preparation, improved feedback during processes, clearer map comparisons, multilingual support, and greater transparency in reports and modelling assumptions would significantly strengthen user experience and practical applicability.</td></tr>
<tr><td>RQ-Acc1</td><td>How useful is ICARIA methodology for the Regional Authorities and other stakeholders?</td></tr>
<tr><td colspan="2">ICARIA’s methodology provides a structured, scenario-based approach to climate adaptation, integrating hazard, exposure, and vulnerability data. It enables consistent evaluation across regions and supports evidence-based decision-making. As such, the methodology seemed to be useful by Regional Authorities and other participating stakeholders. Data preparation complexity and guidance needs remain, but the methodological framework has shown the potential for practical and replicable climate resilience planning.</td></tr>
<tr><td>RQ-Acc2</td><td>How useful are ICARIA solutions for the Regional Authorities and other stakeholders?</td></tr>
<tr><td colspan="2">ICARIA solutions are perceived by Regional Authorities and stakeholders as valuable for climate adaptation and risk management. They enable visualization and comparison of multiple scenarios, assessment of hazards, and exploration of potential impacts across regions. The platform’s intuitive interface could support evidence-based decision-making and strategic planning. While some guidance and data preparation are needed, overall satisfaction by stakeholders is high, and the solutions show strong potential for replicable, cross-sector applications in enhancing resilience.</td></tr>
<tr><td>RQ-Acc3</td><td>Do potential users want to use this type of solutions in their work?</td></tr>
<tr><td colspan="2">Potential users (i.e., participating stakeholders) show clear interest in using ICARIA solutions in their work. Most participants appreciated the scenario comparison, hazard visualization, and impact assessment features as relevant and actionable. While routine daily use may be limited by data preparation complexity and some usability issues, stakeholders, especially from public administrations and infrastructure operators, expressed willingness to adopt the solutions for strategic planning, resilience assessment, and climate adaptation decision-making.</td></tr>
<tr><td>RQ-Acc4</td><td>Which improvements / additional features would make the ICARIA methodology and/or solution(s) significantly more attractive for potential users?</td></tr>
<tr><td colspan="2">ICARIA methodology and solutions would be more attractive with improved onboarding, simpler navigation, clearer chart/map explanations, and non-expert-friendly data guides. Multilingual support, practical examples, and expanded hazard coverage would broaden usability. Enhancing transparency, interoperability, and risk modelling, particularly for cascading effects, alongside intuitive scenario comparisons, would increase stakeholder confidence and adoption across sectors and regions.</td></tr>
<tr><td>RQ-Soc1</td><td>How much socioeconomic impact (including gender and ethics issues) do trial participants anticipate from ICARIA methodology and solutions?</td></tr>
</table>

RQ No.	Research Question
	NOT ADDRESSED
RQ-Soc2	What kind of socioeconomic impacts (including gender and ethics issues) do trial participants anticipate from use of ICARIA methodology and solutions?
	NOT ADDRESSED?

TODO: reflect a bit on what we have learnt now

The answers to the research questions in the table can be summarized as follows.

ICARIA's data and modelling outputs are generally considered plausible and credible within their defined scope, offering innovative integration of hazard, exposure, vulnerability, and resilience assessments. Participants valued the ability to compare multiple scenarios, visualize projections, and explore cross-sectoral impacts, which represents a clear step beyond current regional practices. However, reliability is constrained by prototype maturity, limited multi-hazard and cascading risk coverage, and dependency on available data. Applying the solutions in new regions is technically feasible but moderately demanding where data are scarce, requiring technical expertise and some contextual adaptation. Usability and comprehension were mostly positive, with core workflows such as scenario comparison and data upload intuitive, while advanced functions (RAF/RAT, map analysis, multi-step workflows) sometimes required guidance. Stakeholders, particularly Regional Authorities and infrastructure operators, recognized the solutions' potential for evidence-based planning and climate adaptation, but highlighted the need for clearer instructions, non-expert guidance, enhanced transparency, multilingual support, and improved onboarding. We can conclude that ICARIA demonstrates strong potential for replicable, cross-sector climate resilience planning, with targeted improvements necessary to increase trust, operational usability, and adoption.

As clearly indicated in Table 22 above, the research questions related to sustainability (including some of the Sci- and Acc- questions were only partially resolved and the questions related to socioeconomic impacts weren't resolved at all during the trials. This would be a significant setback if trial events were the end of ICARIA validation, but they aren't. As indicated in Section 3.1, validating the replication potential (RQ-Sci2) and socio-economic impacts (RQ-Soc1 and RQ-Soc2) is the central goal of mini trials and validation of the sustainability continues into final demonstrators and they will also be used to further improve our understanding of the level of interest potential users have at ICARIA results at the end of the project and perceived strengths and weaknesses of the project results compared to the SOTA.

As a result, we can conclude that the trials have produced sufficient evidence to satisfactorily resolve most of the research questions, while the remaining ones will be resolved in the context of mini trials and the final demonstration event.

8.2 General conclusions

Deliverable 4.2 demonstrates the successful integration, testing and validation of the ICARIA risk assessment framework and Decision Support System (DSS) across three diverse European case studies: the Barcelona Metropolitan Area (AMB), the Salzburg Region (SBG), and the South Aegean Region (SAR). The work achieved its two principal objectives: first, to validate the resilience assessment tools and DSS through structured stakeholder trials; and second, to implement single- and multi-hazard risk assessments for critical assets under present and future climate scenarios.

The stakeholder trials conducted in AMB, SBG and SAR confirmed the technical robustness and practical usefulness of the DSS. Participants were able to create and compare scenarios, upload and validate datasets, execute risk and resilience assessments, and visualize spatially explicit results. Across all regions, stakeholders emphasized the added value of integrating climate projections, multi-hazard modelling and adaptation evaluation within a single platform. The capacity to compare Business-as-Usual and adaptation scenarios, and to translate complex modelling outputs into accessible visual information, was particularly appreciated for supporting dialogue between technical experts and decision-makers. While feedback identified areas for improvement—such as clearer explanation of modelling assumptions, enhanced user guidance in resilience modules, and simplified data preparation—these observations reflect the natural refinement process of a research prototype evolving toward operational maturity.

The risk assessments performed within Deliverable 4.2 provide quantitative evidence of climate risk amplification in the three ICARIA case studies.

In the Barcelona Metropolitan Area, compound pluvial–coastal flooding systematically amplifies impacts compared to single-hazard simulations. At the metropolitan scale, multi-hazard conditions increase high-risk pedestrian areas by approximately 4–8%, with local increases exceeding 10% in low-lying coastal neighborhoods. For transport infrastructure, high-risk road length increases by up to 5% overall and by 10–13% in specific coastal municipalities such as Barcelona, Badalona and Castelldefels. For residential and commercial properties, economic damages rise by approximately 4–7% for T10–T100 events and by up to 10–15% in extreme return periods when compound drivers are considered. Expected Annual Damage (EAD) increases by roughly 5% under multi-hazard configurations relative to single-hazard conditions. Furthermore, cascading effects further intensify risk. Under extreme compound events, electricity repair times increase by 15–20%, and the number of affected consumers rises by more than 40%, amplifying indirect economic losses across interconnected sectors. Adaptation measures in AMB demonstrate clear and quantifiable benefits. High-risk pedestrian and transport areas are reduced by 10–12% for T10 events and by 7–10% for higher return periods, while reductions for frequent T1 events reach up to 17–19%. Property damages decrease by 14–18% for T10 events and by 7–10% for extreme storms. Expected Annual Damage declines by approximately 11–15% compared to the multi-hazard baseline.

As an acknowledgement, the ICARIA consortium like to express our sincere gratitude to Ajuntament de Badalona, Ajuntament de Badia del Vallès, Ajuntament de Barberà del Vallès, Ajuntament de Barcelona, Ajuntament de Begues, Ajuntament de Castelldefels, Ajuntament de Castellbisbal, Ajuntament de Cerdanyola del Vallès, Ajuntament de Cervelló, Ajuntament de Corbera de Llobregat,

Ajuntament de Cornellà de Llobregat, Ajuntament d'Esplugues de Llobregat, Ajuntament de Gavà, Ajuntament de l'Hospitalet de Llobregat, Ajuntament de la Palma de Cervelló, Ajuntament del Papiol, Ajuntament del Prat de Llobregat, Ajuntament de Molins de Rei, Ajuntament de Montcada i Reixac, Ajuntament de Montgat, Ajuntament de Pallejà, Ajuntament de Ripollet, Ajuntament de Sant Adrià de Besòs, Ajuntament de Sant Andreu de la Barca, Ajuntament de Sant Boi de Llobregat, Ajuntament de Sant Climent de Llobregat, Ajuntament de Sant Cugat del Vallès, Ajuntament de Sant Feliu de Llobregat, Ajuntament de Sant Joan Despí, Ajuntament de Sant Just Desvern, Ajuntament de Sant Vicenç dels Horts, Ajuntament de Santa Coloma de Cervelló, Ajuntament de Santa Coloma de Gramenet, Ajuntament de Tiana, Ajuntament de Torrelles de Llobregat, and Ajuntament de Viladecans for their commitment, collaboration, and valuable contributions to the development of this work. We also wish to acknowledge the important support provided by Barcelona Cicle de l'Aigua, S.A. (BCASA) and, finally, to extend our special thanks to the Àrea Metropolitana de Barcelona (AMB).

In the Salzburg Region, fluvial flooding and windstorms represent the dominant hazards. Direct flood damages range from approximately €30,000 for 2-year events to about €9 million for 100-year events. Severe windstorms generate losses of approximately €6–7 million in the most exposed western areas of Mittersill. Under multi-hazard simulations (wind-induced debris affecting river roughness), aggregated direct economic losses differ only marginally from single-hazard conditions, generally by less than 5%, although localized flood depth increases of up to 0.5 m are observed along tributaries. However, cascading electricity disruptions reveal significant systemic vulnerability. In the 2038 stress-test wind event, more than 70% of buildings fall into high cascading risk classes. Indirect economic impacts associated with Energy Not Supplied and Additional Generation Costs are concentrated in these zones, demonstrating that rare extreme events—not gradual climate intensification—are the primary drivers of systemic risk in the region. Adaptation scenarios in Salzburg produce substantial reductions. Relocation of flood-prone industrial assets reduces direct flood damages by approximately €2 million for return periods of 30 years and above, corresponding to reductions of 20–25%. Early warning systems significantly decrease traffic-related vulnerability, shifting most assets from high to low or medium risk classes. Strengthened building standards against wind loads reduce direct wind damage from €6–7 million to €0.3–0.6 million, representing reductions of 90–95% under modeled wind speeds and 70–80% under amplified gust sensitivity scenarios. These figures demonstrate that structural reinforcement is particularly effective in reducing both direct and cascading wind-related losses.

In the South Aegean Region, wildfire and heatwave risks exhibit clear intensification under compound and future climate scenarios. In Rhodes, multi-hazard wildfire conditions increase high-risk areas by approximately 5–10% in central and eastern zones where infrastructure, agricultural assets and previous burn scars overlap. Ecological high-risk areas (categories 4–5) expand by roughly 10–15% under future climate pathways. High-risk economic asset areas increase by approximately 5–8% under compound scenarios. Although the mapped direct human risk footprint remains spatially moderate, the 2023 wildfire event—forcing the evacuation of around 19,000 people—demonstrates how cascading disruptions can produce disproportionate socio-economic impacts. In Syros, heatwave risk already affects more than 60% of buildings in high-risk categories under historical conditions. Climate projections maintain or slightly intensify this exposure, confirming structural vulnerability to extreme heat. Adaptation scenarios in SAR show marked effectiveness. In Rhodes, vegetation replacement with less flammable species reduces category 5 ecological risk areas by approximately 30–32% and category 4 areas by around 10%. High-risk economic asset areas decline by about 20% under single-hazard adaptation and by 28–34% under multi-hazard adaptation scenarios. In Syros, building retrofitting reduces the proportion of highly vulnerable buildings by an estimated 25–35%, shifting a significant share into moderate risk categories and reducing the likelihood of cascading service disruptions.

Importantly, the three CS implemented data-gap filling methods based on the contents of Deliverable 1.3 and other alternative sources. In the AMB, the absence of fully detailed infrastructure datasets was overcome through the development and application of a synthetic network methodology based on available spatial, hydraulic and land-use information. In the Salzburg Region, where asset-specific vulnerability data were partially unavailable, flood impact estimation relied on generalized European flood-damage curves from a continental-scale study. Furthermore, the flood economic impact assessment in this region fully relied on the DSS workflow developed based on the methodology developed in the AMB CS. In the South Aegean Region, risk characterization relied on harmonized European datasets, proxy indicators and literature-based vulnerability classifications integrated into the ICARIA framework.

In conclusion, Deliverable 4.2 confirms that the ICARIA framework and DSS provide a robust, integrated and adaptable approach to climate risk assessment and resilience planning. The successful validation across three contrasting European regions demonstrates both methodological reliability and practical applicability. Climate change consistently emerges as a driver of increasing risk, particularly under compound and extreme event conditions. However, the results also demonstrate that well-designed adaptation strategies—whether structural, ecosystem-based or preparedness-oriented—can substantially reduce both direct and indirect losses. The ICARIA system therefore offers a powerful foundation for supporting regional and local authorities in developing forward-looking, evidence-based climate resilience policies.

References

Amores, A., Marcos, M., Carrió, D. S., & Gómez-Pujol, L. (2020). Coastal impacts of Storm Gloria (January 2020) over the north-western Mediterranean. *Natural Hazards and Earth System Sciences*, *20*(7), 1955-1968. https://doi.org/10.5194/nhess-20-1955-2020

Brito, R. S., Cardoso, M. A., Mendes, A., & Oliveira, A. (2026). Climate Resilience Assessment in Regions, Cities, Strategic Services, and Critical Infrastructure: Implementation and Outcomes. *Sustainability*, *18*(1701), 23. https://doi.org/doi.org/10.3390/su18031701

Büegelmayer-Blaschek, M., & Hasel, K. (s. f.). *ICARIA: dynamically downscaled climate projections using two regional climate models*. Recuperado 8 de enero de 2026, de https://zenodo.org/records/14937418

Bügelmayer-Blaschek, M., Hasel, K., Redolat, D., Paradinas, C., & Monjo, R. (2025). Future climate projections for South Aegean and Salzburg region based on statistical and dynamical downscaling—Similarities and discrepancies. *Environmental Research Communications*, *7*(6), 065003. https://doi.org/10.1088/2515-7620/addc3f

Chen, A., Evans, B., De La Cruz–Coronas, A., Russo, B., Büegelmayer-Blaschek, M., & Zarios, I. (2025). *ICARIA Deliverable 2.4: ICARIA multi-hazards modelling tools and application guidelines – Version 2*.

Cosco, C., Gómez, M., Russo, B., Tellez-Alvarez, J., Macchione, F., Costabile, P., & Costanzo, C. (2020). Discharge coefficients for specific grated inlets. Influence of the Froude number. *Urban Water Journal*, *17*(7), 656-668. https://doi.org/10.1080/1573062X.2020.1811881

De La Cruz–Coronas, A., Evans, B., Truchi, A., Addabbo, N., Büegelmayer-Blaschek, M., & Zarikos, I. (2023). *ICARIA Deliverable 2.1: Holistic modeling framework for multi-hazard events*.

De La Cruz–Coronas, À., & Russo, B. (2025). Synthetic Sewer Networks for Pluvial Flood Assessment in Urban Areas: A Data Gap Filling Methodology. *Hydrological Processes*, *39*(12), e70365. https://doi.org/10.1002/hyp.70365

Dunn, S., Wilkinson, S., Alderson, D., Fowler, H., & Galasso, C. (2018). Fragility Curves for Assessing the Resilience of Electricity Networks Constructed from an Extensive Fault Database. *Natural Hazards Review*, *19*(1), 04017019. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000267

Eilander, D., Couasnon, A., Leijnse, T., Ikeuchi, H., Yamazaki, D., Muis, S., Dullaart, J., Haag, A., Winsemius, H. C., & Ward, P. J. (2023). A globally applicable framework for compound flood hazard modeling. *Natural Hazards and Earth System Sciences*, *23*(2), 823-846. https://doi.org/10.5194/nhess-23-823-2023

Estrella, S., Olivares, G., Russo, B., & Sánchez-Juny, M. (2025). *Mezclas bituminosas porosas en el contexto de los SUDS: revisión y perspectivas*.

Feuerstein, B., Groenemeijer, P., Dirksen, E., Hubrig, M., Holzer, A. M., & Dotzek, N. (2011). Towards an improved wind speed scale and damage description adapted for Central Europe. *Atmospheric Research*, *100*(4), 547-564. https://doi.org/10.1016/j.atmosres.2010.12.026

Flor Tey, G., Martínez-Gomariz, E., Russo, B., & Bosque Royo, J. (2025). Metodología para la cuantificación económica de daños tangibles directos provocados por inundaciones en estaciones depuradoras de agua residual. Aplicación en el Área Metropolitana de Barcelona. *Ingeniería del Agua*, *29*(4), 263-279. https://doi.org/10.4995/ia.2025.24361

Fonio, C., Widera, A., & Zwęgliński, T. (2023). *Innovation in Crisis Management. London.*

Guerrero-Hidalga, De La Cruz–Coronas, Flor, G., Evans, B., & Gili, A. (2024). *ICARIA Deliverable 3.1 Tangible Impact Assessment Methods*.

Haiden, T., Kann, A., Wittmann, C., Pistotnik, G., Bica, B., & Gruber, C. (2011). The Integrated Nowcasting through Comprehensive Analysis (INCA) System and Its Validation over the Eastern Alpine Region. *Weather and Forecasting*, *26*(2), 166-183. https://doi.org/10.1175/2010WAF2222451.1

Havlik, D., Fotcha, V., De La Cruz–Coronas, À., Büegelmayer-Blaschek, M., & Zarikos, I. (2024). *ICARIA Deliverable 4.1: Trial Design*.

Insa. (2025). *Study and assessment of adaptive measures to the impact of coastal flooding hazard on the Llevant Main Sewer (Barcelona, Spain)*. Universitat Politècnica de Catalunya.

IPCC. (2023a). *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (1.ª ed.). Cambridge University Press. https://doi.org/10.1017/9781009157896

IPCC (Ed.). (2023b). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (1.ª ed., pp. 953-1048). Cambridge University Press. https://doi.org/10.1017/9781009157926.011

Katragkou, E., Sobolowski, S. P., Teichmann, C., Solmon, F., Pavlidis, V., Rechid, D., Hoffmann, P., Fernandez, J., Nikulin, G., & Jacob, D. (2024). Delivering an Improved Framework for the New Generation of CMIP6-Driven EURO-CORDEX Regional Climate Simulations. *Bulletin of the American Meteorological Society*, *105*(6), E962-E974. https://doi.org/10.1175/BAMS-D-23-0131.1

Koks, E. E., & Haer., T. (2020). A high-resolution wind damage model for Europe. *Scientific Reports*, *10*(1), 6866. https://doi.org/10.1038/s41598-020-63580-w

Leijnse, T., Van Ormondt, M., Nederhoff, K., & Van Dongeren, A. (2021). Modeling compound flooding in coastal systems using a computationally efficient reduced-physics solver: Including fluvial, pluvial, tidal, wind- and wave-driven processes. *Coastal Engineering*, *163*, 103796. https://doi.org/10.1016/j.coastaleng.2020.103796

Leone, M. F., Zuccaro, G., De Gregorio, D., Turchi, A., Tedeschi, A., Büegelmayer-Blaschek, M., Sfetsos, A., Zarikos, I., Coronas, A. D. L. C., & Russo, B. (2025). A holistic asset-level modelling framework for a comprehensive multi-hazard risk/impact assessment: Insights from the ICARIA project. *International Journal of Disaster Risk Reduction*, *119*, 105319. https://doi.org/10.1016/j.ijdrr.2025.105319

Locatelli, L., Guerrero, M., Russo, B., Martínez-Gomariz, E., Sunyer, D., & Martínez, M. (2020). Socio-Economic Assessment of Green Infrastructure for Climate Change Adaptation in the Context of Urban Drainage Planning. *Sustainability*, *12*(9), 3792. https://doi.org/10.3390/su12093792

Ma, N., Xu, Z., Wang, Y., Liu, G., Xin, L., Liu, D., Liu, Z., Shi, J., & Chen, C. (2024). Strategies for Improving the Resiliency of Distribution Networks in Electric Power Systems during Typhoon and Water-Logging Disasters. *Energies*, *17*(5), 1165. https://doi.org/10.3390/en17051165

Martínez-Gomariz, E., Forero-Ortiz, E., Guerrero-Hidalga, M., Castán, S., & Gómez, M. (2020). Flood Depth-Damage Curves for Spanish Urban Areas. *Sustainability*, *12*(7), 2666. https://doi.org/10.3390/su12072666

Martínez-Gomariz, E., Forero-Ortiz, E., Russo, B., Locatelli, L., Guerrero-Hidalga, M., Yubero, D., & Castan, S. (2021). A novel expert opinion-based approach to compute estimations of flood damage to property in dense urban environments. Barcelona case study. *Journal of Hydrology*, *598*, 126244. https://doi.org/10.1016/J.JHYDROL.2021.126244

Martínez-Gomariz, E., Gómez, M., & Russo, B. (2016). Experimental study of the stability of pedestrians exposed to urban pluvial flooding. *Natural Hazards*, *82*(2), 1259-1278. https://doi.org/10.1007/s11069-016-2242-z

Martínez-Gomariz, E., Gómez, M., Russo, B., & Djordjević, S. (2017). A new experiments-based methodology to define the stability threshold for any vehicle exposed to flooding. *Urban Water Journal*, *14*(9), 930-939.

Martínez-Gomariz, E., Guerrero-Hidalga, M., Russo, B., Yubero, D., Gómez, M., & Castán, S. (2019). Desarrollo y aplicación de curvas de daño y estanqueidad para la estimación del impacto económico de las inundaciones en zonas urbanas españolas. *Ingeniería del agua*, *23*(4), 229. https://doi.org/10.4995/ia.2019.12137

Martínez-Gomariz, Eduardo, Locatelli, L., Guerrero, M., Russo, B., & Martínez, M. (2019). Socio-Economic Potential Impacts Due to Urban Pluvial Floods in Badalona (Spain) in a Context of Climate Change. *Water*, *11*(12), 2658. https://doi.org/10.3390/w11122658

Nirandjan, S., Koks, E. E., Ye, M., Pant, R., Van Ginkel, K. C. H., Aerts, J. C. J. H., & Ward, P. J. (2024). Review article: Physical vulnerability database for critical infrastructure hazard risk assessments – a systematic review and data collection. *Natural Hazards and Earth System Sciences*, *24*(12), 4341-4368. https://doi.org/10.5194/nhess-24-4341-2024

Olivares-Cerpa, G., Russo, B., Martínez-Puentes, M., Bladé, E., & Sanz-Ramos, M. (2022). "SUDS-lineales" para reducir el riesgo de inundación considerando escenarios de Cambio Climático. *Ingeniería del Agua*, *26*(2), 77-90. https://doi.org/10.4995/ia.2022.17058

Oom, D., Rigo, D. de, Pfeiffer, H., Branco, A., Ferrari, D., & Grecchi, R. (with Europäische Gemeinschaften). (2022). *Pan-European wildfire risk assessment*. Publications Office of the European Union. https://doi.org/10.2760/9429

Ortiz, A., Velasco, M. J., Esbri, O., Medina, V., & Russo, B. (2020). The Economic Impact of Climate Change on Urban Drainage Master Planning in Barcelona. *Sustainability 2021, Vol. 13, Page 71*, *13*(1), 71. https://doi.org/10.3390/SU13010071

Paradinas Blázquez, C., Büegelmayer-Blaschek, M., Galiano Sánchez, L., Redolat Negro, D., Prado López, C., Hasel, K., Züger, J., Lampert, J., & Thiele, P. (2024). *ICARIA Deliverable 1.2: Climate projections and hazard scenarios* (p. 210).

Russo, B., Coronas, À. de la C., Leone, M., Evans, B., Brito, R. S., Havlik, D., Bügelmayer-Blaschek, M., Pacheco, D., & Sfetsos, A. (2023). Improving Climate Resilience of Critical Assets: The ICARIA Project. *Sustainability*, *15*(19), 14090.

Russo, B., Gómez, M., & Macchione, F. (2013). Pedestrian hazard criteria for flooded urban areas. *Natural Hazards*, *69*(1), 251-265. https://doi.org/10.1007/S11069-013-0702-2/METRICS

Russo, B., Sunyer, D., Velasco, M., & Djordjević, S. (2015). Analysis of extreme flooding events through a calibrated 1D/2D coupled model: The case of Barcelona (Spain). *Journal of Hydroinformatics*, *17*(3), 473-491. https://doi.org/10.2166/hydro.2014.063

Russo, B., Valentín, M. G., & Tellez-Álvarez, J. (2021). The Relevance of Grated Inlets within Surface Drainage Systems in the Field of Urban Flood Resilience. A Review of Several Experimental and Numerical Simulation Approaches. *Sustainability*, *13*(13), 7189. https://doi.org/10.3390/su13137189

Russo, B., Velasco, M., Locatelli, L., Sunyer, D., Yubero, D., Monjo, R., Martínez-Gomariz, E., Forero-Ortiz, E., Sánchez-Muñoz, D., Evans, B., & Gómez, A. G. (2020). Assessment of urban flood resilience in Barcelona for current and future scenarios. The RESCCUE project. *Sustainability (Switzerland)*, *12*(14). https://doi.org/10.3390/su12145638

Sánchez-Muñoz, D., Domínguez-García, J. L., Martínez-Gomariz, E., Russo, B., Stevens, J., & Pardo, M. (2020). Electrical Grid Risk Assessment Against Flooding in Barcelona and Bristol Cities. *Sustainability 2020, Vol. 12, Page 1527*, *12*(4), 1527. https://doi.org/10.3390/SU12041527

Truchi, A., Tedeschi, A., Bügelmayer-, M., Sfetsos, A., De La Cruz–Coronas, A., & Havlik, D. (2023). *D5.4 Stakeholder Engagement Plan*.

Truchi, A., Tedeschi, A., Leone, M. F., De Gregorio, D., Zuccaro, G., De La Cruz–Coronas, A., Büegelmayer-Blaschek, M., & Zarikos, I. (2023). *ICARIA Deliverable 1.1: ICARIA holistic modelling framework*.

UNDRR. (2015). *Sendai Framework for Disaster Risk Reduction 2015–2030* (p. 37). https://www.undrr.org/media/16176/download?startDownload=20250107

UNDRR. (2020). *Human cost fo disasters: An overview of the last 20 years*. https://www.undrr.org/publication/human-cost-disasters-overview-last-20-years-2000-2019

Velasco, M., Russo, B., Cabello, À., Termes, M., Sunyer, D., & Malgrat, P. (2016). Assessment of the effectiveness of structural and nonstructural measures to cope with global change impacts in Barcelona. *Journal of Flood Risk Management*, *11*(51), S55-S68. https://doi.org/10.1111/jfr3.12247

World Bank. (2025). *A Global Assessment of Building Codes: Current Status and Evolving Needs to Promote Resilient, Green and Inclusive Buildings*. http://hdl.handle.net/10986/43310

Annex A – Data management statement

Table A.1. Data used in preparation of ICARIA Deliverable 4.2

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
Join provability assessment	excel	>10GB	Open data	Climate risk assessment	10.5281/zenodo.17455541

Table A.2. Data produced in preparation of ICARIA Deliverable 4.2

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.18633204
SAR CS risk assessment results	SHP and TIFF	>10GB	Open data	Asset-level risk assessment	10.5281/zenodo.18709629
AMB CS risk assessment results	SHP and TIFF	>10GB	Not public	Asset-level risk assessment	na

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