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Climate Resilience Assessment in Regions, Cities, Strategic Services, and Critical Infrastructure: Implementation and Outcomes

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Abstract

Resilience to climate change is a complex concept, especially in metropolitan areas where diverse services and stakeholders interact. Promoting sustainable climate adaptation, a resilience assessment method focused on regional areas and nature-based solutions is presented, along with its open-access, web-based platform, supporting resilience assessment, planning, and monitoring. Floods, droughts, heat or cold waves, windstorms, and forest fires can be assessed. A framework for holistic assessment and other framework, addressing critical infrastructure, are integrated. Four resilience dimensions are assessed: organizational (governance, social aspects, finance); spatial (exposure, impacts, and mapping); functional (service management, interdependencies); and physical (infrastructure robustness, redundancy). Strategic services comprise, e.g., water, waste, and natural areas. Resilience capacities, e.g., to prevent, respond, and recover from disruptions, are also assessed. The paper emphasizes new developments and assessment. Practical step-by-step guidance aligned with assessment purposes is included, aiming to address observed limitations (e.g., fragmented service provision, communication silos, data constraints). Overall results of a Spanish metropolitan area (AMB) and an exploratory application to an Austrian rural case (SLR) are also presented. Following the guidelines, AMB progressed from an essential to a comprehensive assessment. Overall, almost 1/3 of the metrics are advanced or progressing. SLR assessed its resilience capabilities regarding electrical infrastructure.

Keywords: assessment; climate change; critical infrastructure; framework; regional; resilience; urban; web platform

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Academic Editor: David Pastor-Escuredo

Received: 15 December 2025
Revised: 27 January 2026
Accepted: 30 January 2026
Published: 6 February 2026

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1. Introduction

1.1. Urban and Regional Resilience

Resilience is a multidimensional concept, encompassing a wide range of perspectives and challenges. In the context of urban regions and metropolitan areas, this is amplified. These areas are dynamic, interconnected, and full of competing needs and complexities.

This interconnectedness of strategic services and assets requires seamless collaboration among diverse stakeholders to be effectively managed and protected.

The concept of resilience has evolved across disciplines and time [1–5]. Resilience capabilities can be understood as the ability of human settlements to *withstand* and *recover* quickly from an event while maintaining essential functions, and *adapt* after it, preferably to a better state. Withstanding and recovering are strongly linked to autonomy, flexibility, redundancy, and resilience awareness from the different stakeholders. Resilience to disruptive events includes reducing risks and damage from disasters by *anticipating* and being *prepared* for them. This regards either deliberate human actions, accidents, or natural hazards, whether they come as acute shocks or as slow changes in circumstances. Adaptation is crucial for anticipation and preparedness, as it includes learning from past events and using that experience to inform future actions. This is a continuous improvement cycle, as preparedness is key to better withstanding a future event. The whole resilience cycle (withstand–recover–adapt–anticipate–prepare) applies to interconnected social, economic, and ecological systems and ensures long-term sustainability, security, and well-being. Strengthening the resilience of all systems is more important than ever, as ecosystems and human societies grow increasingly interconnected, urban areas cluster into larger linked regions, with cascading events rippling back and forth, namely those driven by climate change (CC) [6].

1.2. Resilience to Climate Change

Climate hazards and events—such as intense rainfall, sea level rise, droughts, and heat waves—can have severe impacts on essential services, people, the environment, and the economy, which are exacerbated in the case of compound or cascading events. As CC intensifies, hazardous events are becoming more frequent and severe worldwide, emphasizing the urgent need for sustainable urban development and integration of resilience in territorial planning and infrastructure design, operation, and planning. CC poses additional challenges, especially for large metropolitan areas with densely populated areas [7].

To promote resilience, it is crucial for governments, the private sector, civil society, and other stakeholders to better understand how actions affecting social, ecological, and economic well-being interact and strengthen or weaken resilience [6]. The EU adaptation strategy introduces the concept of "just resilience", highlighting that CC impacts are unevenly felt across different groups. Achieving fair and inclusive resilience is essential to ensure equitable distribution of climate adaptation benefits. The EU mission on climate adaptation aims to accelerate transformation to climate resilience through inclusive governance and actions that protect vulnerable populations [8].

The IPCC Sixth Assessment Report (AR6) [7] stresses that resilience should be measured not only by reduced direct impacts of mitigation actions, but also by their ability to cut greenhouse gas (GHG) emissions and to deliver social, environmental, and economic co-benefits. AR6 builds on climate models that use the Shared Socioeconomic Pathways (SSPs). SSPs describe how global society, population, and the economy may change over the next century, and are used to explore how different societal choices affect GHG emissions and whether the Paris Agreement's climate goals can be achieved. First published in 2016, SSPs have only recently been widely applied in climate modeling [7].

The European Water Resilience Strategy underpins that water resilience is both a climate-adaptation and a competitiveness issue: managing water well boosts environmental security, economic strength, and Europe's capacity to face future shocks [9].

Resilience assessment is particularly important for critical infrastructure. The European Directive 2008/114/EC (ECI Directive) required each Member State to identify infrastructure essential for society's vital functions, such as health, security, and economic

or social well-being. This Directive has now been replaced by the CER (Critical Entities Resilience) Directive (EU 2022/2557), which defines resilience as a critical entity's ability to prevent, protect, respond to, resist, mitigate, absorb, and recover from incidents.

1.3. Resilience Assessment

By assessing current and future resilience, cities and regions are provided with a baseline for understanding their present situation, guiding decisions on strategies, actions, and measures for long-, medium-, and short-term planning, and enabling progress evaluation [10,11]. As resilience is shaped by the interaction of multiple systems, CC resilience assessments benefit from considering not only a system's own capacity to cope with natural hazards, but also the collective capacity of the wider urban or regional context.

Growing recognition of resilience's importance has led to the creation of various tools and frameworks for its assessment, developed across multiple disciplines. Their goal is to support managers, planners, and decision-makers in identifying areas for improvement, prioritizing interventions, defining resilience strategies, developing action plans, and monitoring the effectiveness and efficiency of their implementation [10]. Some were developed by international organizations, such as those by ICLEI, UN-Habitat, and the World Bank, among others [11]. Others were produced through European Union-funded projects, e.g., the EU-Circle Resilience Assessment Tool [12], the RESCCUE RAF App [11], or Resiloc [13], each with its specific focus, structure, and method for assessing resilience. Until 2009, research published on urban resilience assessment was quite limited and fragmented, mainly focusing on risk mitigation and robustness. In the next decade, assessments evolved towards including reliability and vulnerability and more adaptation-oriented approaches (e.g., climate change adaptation and flood resilience), and more attention has been paid to infrastructural, institutional, and environmental aspects at the expense of social and economic dimensions [14]. Major gaps were related to assessing resilience against socio-economic and health risks, beyond the city scale, and a major limitation was the fact that robust, holistic frameworks were mostly not available as free access tools [11,14,15]. Additionally, a comprehensive, objective-driven assessment has yet to be developed—one that evaluates the resilience of a single urban sector while simultaneously accounting for its interdependencies with other sectors and its contribution to the wider urban system. This gap was addressed in [11], grounded in existing metrics and frameworks, bridging the gaps and needs identified for its scope, and allowing a wider application to different resilience maturity levels. However, the assessment in [11] still did not incorporate natural areas as a strategic service, nor did it simultaneously address the multiple hazards they face or adopt a regional perspective.

The UN-Habitat resilience dimensions [16] are a comprehensive approach specifically designed for cities that provides both an overview of the city as a whole and of each service in particular, by considering the resilience dimensions (*organizational*, *spatial*, *functional*, and *physical*). These were later used in the RESCCUE framework for several urban services [11]. The RESCCUE resilience assessment framework (RAF) provides an objective-driven diagnosis based on the degree of compliance with resilience objectives across these four dimensions: *organizational* (regarding city or regional governance, social and stakeholder aspects, finances, planning instruments), *spatial* (concerning urban space and environment, risk mapping, spatial exposure, and impacts to climate hazards), *functional* (dedicated to governance of the strategic services, its planning and risk management, its flexibility, autonomy and interdependencies, and its preparedness to respond, endure, and build back from stressful CC events), and *physical* (specific for service infrastructure, its assets' criticality, robustness, autonomy, and redundancy). The first two dimensions are primarily the responsibility of the city or regional managers, while the latter two are

handled by several utilities, for water, wastewater, stormwater, waste, energy, and mobility strategic services and infrastructures, reinforcing the need for a multi-stakeholder assessment. It should be noted that the *functional* dimension encompasses, from the utility perspective, several concerns that are included in the *organizational* dimension for the city (or regional) perspective.

RESCCUE RAF follows a hierarchical tree structure (Objectives–Criteria–Metrics). Within each dimension, resilience objectives are assessed through criteria that reflect different perspectives. Each criterion is quantified by metrics, and each metric is evaluated against reference values. These reference values provide thresholds to enable judgment of the answer provided by the user. In this framework, all metrics function as performance indicators, meaning that they are standardized and comparable between systems, cities, or for different scenarios or time frames. Metric responses can be selected from a predefined list, which was defined based on the reference values previously mentioned and relate to a development level (*incipient*, *progressing*, or *advanced*). The tree structure, each metric, and its reference values and set of answers were submitted to a stakeholder validation procedure, defined and applied in the RESCCUE project [17,18].

Time is also embedded in the metrics, as they implicitly capture the city's ability to prepare for, respond to, and recover from CC events or changing circumstances. Considering different scenarios for the assessment incorporates the uncertainty of resilience evolution over time. To allow a step-by-step assessment, metrics are assigned an *analysis level* (depending on the assessment purpose: *strategic*, *tactical*) and a *relevance level* (depending on the assessment maturity: *essential*, *complementary*, *comprehensive*, following more in-depth requirements) [17].

The final assessment is based on the achievement of the resilience objectives, which is determined by the percentage of metrics in each development level (incipient, progressing, or advanced) for each criterion, objective, service, or dimension.

Resilience depends on the specific context of each city and service. To account for this, the RESCCUE RAF uses city and service profiles that summarize relevant contextual information to support the interpretation of metric results. The city profile provides a unique characterization of the city, covering geography, climate, population, economy and governance, built environment and infrastructure, and climate-related hazards. It also identifies the services to be assessed. The service profile then details each service in a consistent way, describing its context, infrastructure, utilities involved, customer types, assets, and climate-related risks.

1.4. Assessing Resilience in ICARIA Project

Aiming to contribute to a better understanding of the climate-related impacts and the possible risk reduction through sustainable and cost-effective adaptation solutions, the ICARIA project [19] proposed a holistic resilience assessment method focused on resilience of regional areas, facing complex climate events, and on nature-based solutions. This approach is delivered through a web-based free access platform to leverage assessment, planning, and monitoring of resilience to flooding, drought, heat or cold waves, windstorms, and forest fires. This platform is not intended for modeling climate impacts or the effects of strategies. It is used to combine information coming from different sources, contributing to support decision-making. Modeling, planning instruments, or stakeholder engagement actions can be developed prior to or during the assessment, and their results can improve the inputs to the resilience platform.

This paper presents ICARIA's holistic resilience assessment framework and its associated tool. Guidelines for a performing resilience assessment, using this framework, were proposed and were used, explored through the application to a Spanish case study

(Barcelona Metropolitan Area). A pilot application of ICARIA's critical infrastructure tool to an Austrian case study (Salzburg Region) is also made. Emphasizing practical guidance, this paper does not elaborate on the development process of the frameworks and the tools. Links to a decision support system (DSS) and improvement and replicability opportunities are discussed.

2. Materials and Methods

2.1. ICARIA Resilience Assessment

This research work aimed to develop a framework for resilience assessment with a regional scope, including urban services and natural areas and their interdependencies, namely for climate hazards. Additionally, validation with case studies was implemented, and contributions to a decision support system and guidance for practical application were proposed. The developed work was based on several premises. First, relevant research on resilience assessment already exists, and building upon existing frameworks is more effective than developing a new framework from scratch. Secondly, frameworks originally designed for the city scale can be expanded to the regional scale by incorporating additional considerations, to include social concerns, and to natural areas which can be regarded as providers of services, namely ecosystem services. Furthermore, the validation of a holistic assessment framework is best achieved through the involvement of stakeholders. Finally, resilience assessment represents a valuable contribution to decision-making, while its development is a complex process that involves multiple stakeholders and therefore requires appropriate guidance.

Based on an updated literature review and building on the resilience method and tool from RESCCUE, the RAF [11,18] approach was revised and expanded, addressing the ICARIA project's goal regarding climate hazards, geographic scale, and themes. The scope is resilience to CC—other drivers, such as earthquakes, economic crises, or cyberattacks, are excluded. The emphasis is on regional, city, and critical infrastructure resilience, while social and political dimensions are only addressed when they significantly affect overall resilience.

Another resilience tool was used in the ICARIA project, the EU-Circle RAT [12], specifically for critical infrastructure, and it was also included in the project's platform for resilience assessment [20].

Given the particular scope of application and complementarity of the RAF and the RAT, both frameworks and tools were kept as stand-alone solutions. Although both assess overlapping topics, their focus differs: the RAF provides a holistic view of city resilience, covering all services' infrastructure, while the RAT focuses specifically on critical infrastructure within a service.

The gaps between the available frameworks [1–4,6,10,11,14–16] and the ICARIA's scope were assessed [20]. Each framework required specific adaptations—for example, extending the RAF to cover forest fires as a hazard, natural areas as a service, and including regional assessments. Existing metrics were re-examined to broaden their applicability and ensure alignment with ICARIA's objectives. Regarding the RAF, this process involved thorough revision with particular attention to the inclusion of social sciences and humanities concerns [21], as well as an emphasis on capturing resilience to compound events—those arising from two or more natural hazards. Such events may occur simultaneously (compound coincident), follow one another in sequence (compound consecutive), or interact with long-term trends described by SSPs [21]. The assessment remains objective-driven, meaning that it is based on compliance with the RESCCUE resilience objectives across the four dimensions (organizational, spatial, functional, and physical). To ensure alignment, many metrics were kept from the previous projects [20,22]. The analysis is based on the

percentage of metrics assigned to each development level: *incipient* (graded 0 to 1), *progressing* (1 to 2), or *advanced* (2 to 3). The Objective–Criteria–Metrics tree structure enables a bottom-up consideration of these levels to evaluate each criterion, objective, service, and dimension, in a similar way [18]. Regarding the RAT, assessment remains focused on resilience capabilities (withstand–recover–adapt–anticipate–prepare).

The ICARIA resilience method is available on a free-access web-based platform, including both frameworks, in specific apps. Combined, they provide both a holistic assessment and an assessment focused on critical infrastructure. The holistic resilience assessment includes: all climate hazards studied in the project, namely flooding (rain induced, fluvial, and coastal), drought, heat wave, cold wave, windstorm, and forest fire; both urban and regional scales; impact on people, buildings, the natural and the urbanized spaces; and various urban services and assets (water supply, wastewater, stormwater, waste, energy, mobility, and natural areas).

The main purposes of the ICARIA resilience assessment method are to

- Provide a holistic CC resilience diagnosis of the regions, cities, and strategic urban sectors, following an objective-driven approach [23];
- Provide a structured diagnosis of the critical infrastructure or the critical urban sectors in the region and city, following a resilience capacities-driven approach;
- Identify data gaps and areas for resilience improvement;
- Guide the development of an assessment tailored to each critical asset or service, region, or city;
- Support risk-informed decision-making by comparing the contribution to resilience of different measures and strategies;
- Support resilience action planning;
- Monitor the progress of resilience over time;
- Facilitate communication among stakeholders.

To achieve these objectives, the ICARIA resilience method was based on (i) revision, update and upgrade of the RESCCUE RAF and EU-Circle RAT, into ICARIA RAF and ICARIA RAT; (ii) development of the ICARIA resilience platform, which embraces two tools, the upgraded RAF App and RAT App; (iii) preparation of guidelines for application of the RAF framework and tool; (iv) configuration of the connection to a decision support system (DSS); (v) application to case studies. Steps (i) to (iii) were presented as a project deliverable [20]. The current paper presents the upgrades and details of step (iii), after application by the case studies, and focuses on steps (iv) and (v), namely, in the interpretation of the results of resilience assessment.

2.2. Holistic Resilience Assessment

The ICARIA RAF maintains RESCCUE's hierarchical tree structure (resilience dimensions, unfolding into objectives, criteria, and metrics) while adapting it to ICARIA's broader scope. It preserves a step-by-step approach—*essential*, *complementary*, and *comprehensive* relevance levels for the metrics—allowing tailored assessments by region, city, or service, depending on its maturity. Additionally, a metric might be *strategic* or *tactical*, depending on the required analysis level.

ICARIA RAF expands the framework to include natural areas, regional assessments, and additional hazards (e.g., forest fires, specific types of flooding), as well as housing and tourism. More in-depth social aspects are integrated mostly through existing profiles and metrics. Housing was previously considered via metrics related to impacts in urban footprint, and tourism is now included with other economic activities.

A specific and deeper development was required to include the natural areas [21]. Natural areas play a multifaceted role in building resilience to CC. Tree canopies reduce

wind and moderate temperature by reducing solar radiation reaching the ground, shrubs and hedges provide shelter, mulch enriches the soil with humus, and roots, in partnership with mycorrhizae, create pathways that allow water to infiltrate. This effect is amplified when native flora is present, as these species are specially adapted to anchor ravines, thrive along riverbanks and dunes, survive local pests, and withstand droughts and extreme temperature fluctuations. To fully consider their governance, management, and operational aspects, natural areas were thought of as a strategic service. Its assets (forests, gardens, green roofs, lakes, dune ridges) should be given the conditions to thrive and self-sustain, or else be taken care of, maintained, and protected. They have specific functions, namely several ecosystem services like climate regulation, provision of resources, support of habitats and biodiversity, health benefits, and cultural contributions to well-being [24].

In the RAF, some metrics were adapted from existing frameworks (UNDRR, RESCCUE), while many others were newly developed. A new information layer links each metric to its data source or usefulness, ensuring common data formats, consistency, and comparability. Namely, this layer identifies whether the metric relates to modeling activities, assessment scenarios, or critical infrastructure, whether it has a social perspective, or is relevant for a DSS. These modifications and new developments were validated by stakeholders, namely regarding their relevance, applicability, and data availability [25,26]. Stakeholders considered it more difficult to validate the metrics regarding interdependencies with other services, infrastructure autonomy, and both services' and assets' preparedness for recovery and build-back, due to their own lack of data.

Finally, the RAF *organizational* and *spatial* dimensions were fully revised to incorporate social sciences and humanities perspectives within ICARIA's objectives.

The details on the RAF upgrades can be found in [20].

The full resilience assessment framework can be found in Supplementary File S1.

2.3. Resilience Web Platform

A shell was created to accommodate the resilience assessment web platform, lodging both resilience assessment tools, the ICARIA RAF App and the ICARIA RAT. In Figure 1, the front page of the shell is presented, available at https://icaria.lnec.pt/ (accessed on 29 January 2026).

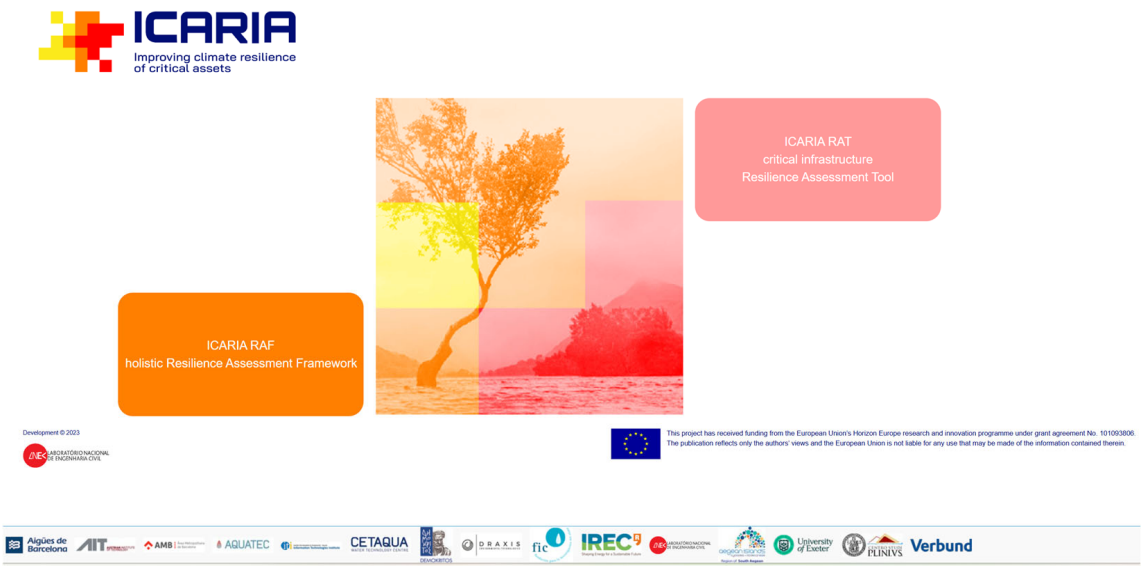


Figure 1. ICARIA shell providing access to both resilience assessment tools.

The shell is built with the Django framework (version 4.2.3) in Python (version 3.9.6), which provides tools for database and software development. The ICARIA RAF App and the RAT tool are embedded in the shell using HTML and JavaScript.

Access to the RAF App is available via the lower-left panel of the shell (Figure 1) and requires user registration (username and password). The RAT tool, accessible in the upper-right panel, does not require registration.

Within the RAF App, users create studies that remain private to their account. When setting up a study (see Figure 2), users select the dimensions to assess (organizational, spatial, functional, and physical) and, within the functional and physical dimensions, the services to be evaluated (water, wastewater, stormwater, waste, energy, mobility, and natural areas). Subsequent tabs (in the horizontal orange line, Figure 2) display the RAF structure of the chosen dimensions and services.

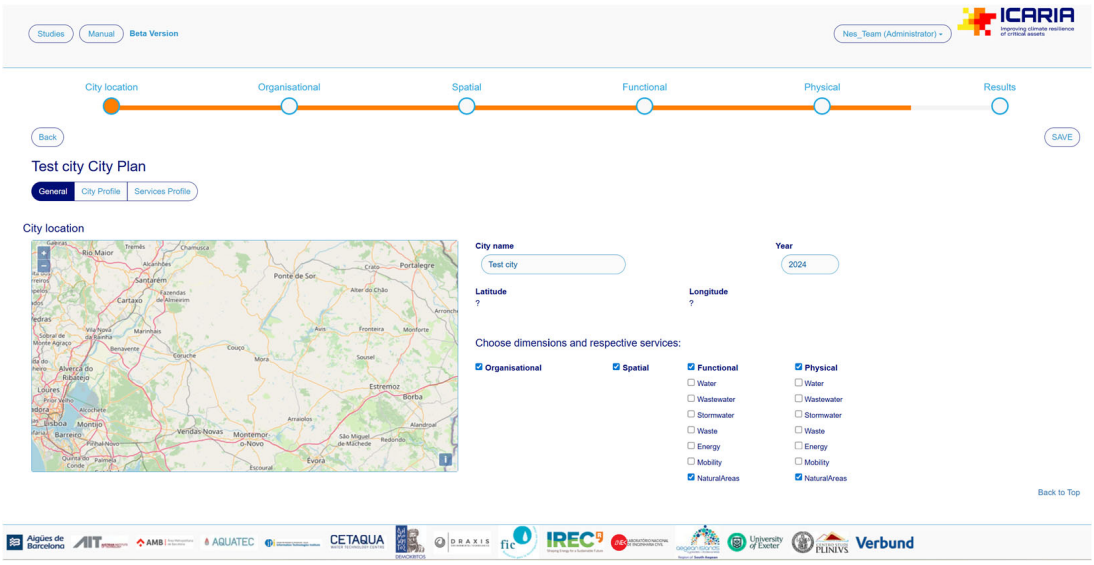


Figure 2. Front page of the ICARIA RAF App.

Filters can be used to select a particular set of metrics, which may correspond to a particular criterion, objective, metric's relevance level, or additional information (in the "Additional Info" tag). For each metric, predefined response options are made available to facilitate input (Figure 3).

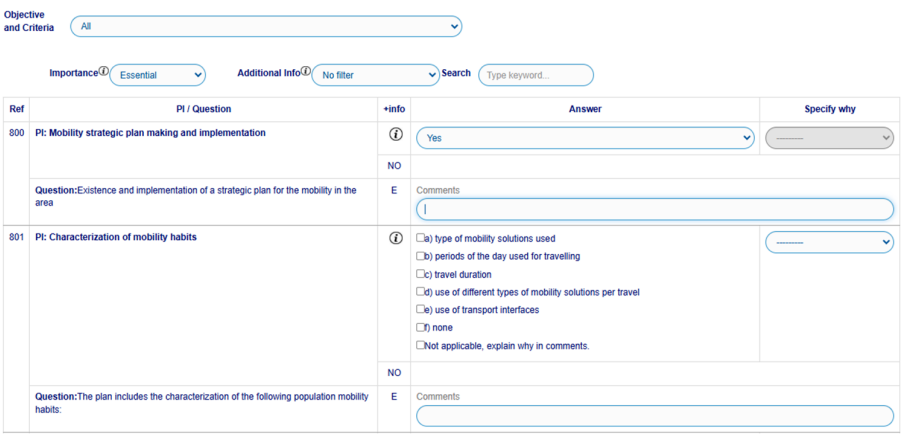
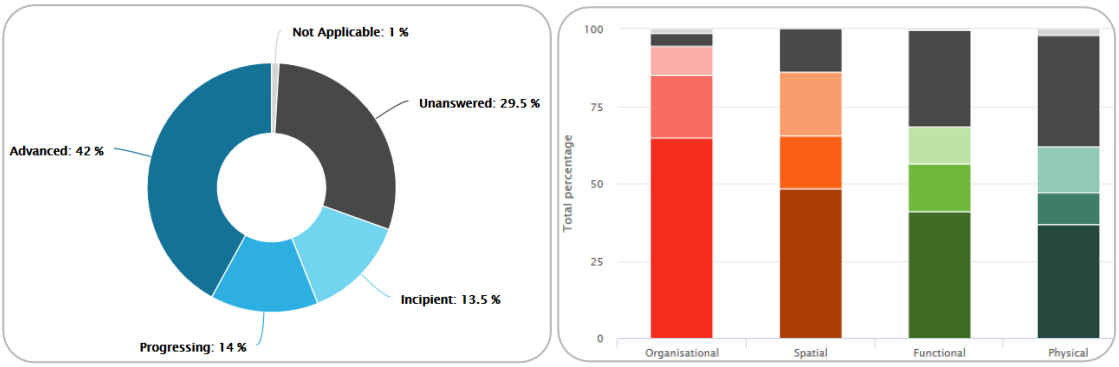


Figure 3. Example of ICARIA RAF App data input.

The ICARIA resilience assessment method is not intended to produce a single global resilience indicator. Instead, it supports multidimensional decision-making, recognizing that regions differ in context, hazards, services, and resilience maturity and concerns.

The RAF App includes a Results module (top right, in Figure 2) with user-friendly, dynamic visualizations at any level of analysis—whole area, dimension, service, objective, or criterion. For each study, it reports the percentage of metrics achieved at each development level (Figure 4). In each graph, colors indicate what is being assessed: blue for the overall area, red for organizational, orange for *spatial*, light green for *functional*, and petroleum green for *physical* dimensions. Shade intensity represents development level (dark = *advanced*, medium = *progressing*, light = *incipient*). This enables progressively deeper insights into resilience: *advanced* results highlight strengths, *progressing* results indicate opportunities for improvement, and *incipient* results reveal key challenges.



(**a**) Overall results (**b**) Development levels for each dimension

Figure 4. RAF App results: example of a regional integrated assessment.

The RAF App supports monitoring resilience by comparing assessments across years and tracking changes in development levels. It can also compare the impact of planned actions on future resilience. A predefined summary report with key graphs is available.

2.4. Guidelines for Application of the Holistic Framework and Tool

Knowledge about resilience at the regional level is limited due to the involvement of multiple administrations. Effective implementation of resilience assessment requires a collaborative process involving multiple stakeholders. This ensures the use of the best available information, integrates diverse perspectives, and strengthens awareness of resilience dimensions, interdependencies, and each organization's contribution to the overall resilience.

Successful application of the RAF depends on strong coordination and a clear step-by-step approach [20]. Overall, the steps to be taken are shown in Figure 5 and detailed below. The main path is shown in darker arrows. Interactive connections are shown in lighter arrows.

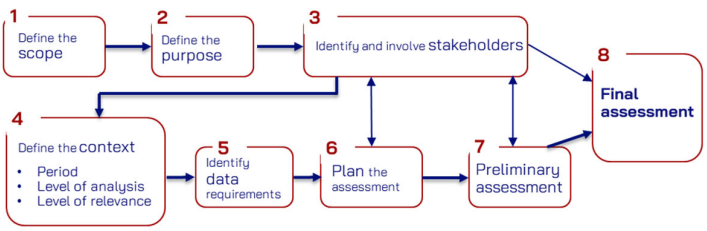


Figure 5. Step-by-step implementation of a holistic resilience assessment using the ICARIA RAF.

Step 1. Define the scope of the assessment, i.e., the geographical area, hazards, services, and infrastructure to be covered. Fill in the city profile and/or the service(s) profile(s).

Step 2. Define the purpose of the assessment.

Step 3. Identify and involve stakeholders relevant to the scope and the purpose, assemble teams, assign responsibilities, and establish guiding principles for cooperation and coordination. Define a coordinator for the assessment.

Step 4. Define the context of the application, including the time period, the analysis level (*strategic* or *tactical*), and the relevance level (*essential*, *complementary*, or *comprehensive*).

Step 5. For each dimension/service/type of infrastructure of the assessment, identify data requirements and select analytical tools to support the application; use the filter on Modeling and on Scenarios to identify the aspects that might require more complex data sets and previous work.

Step 6. Establish a program for the application of the RAF by each member of the team, with assigned responsibilities and a timeline.

Step 7. Perform the preliminary assessment and evaluate the results in the RAF App. This ought to be done by the coordination team and informed to the team members.

Step 8. Using feedback from the team, prepare the final version of the assessment.

Feedback loops should be considered whenever applicable or deemed necessary by the team members.

Practical step-by-step guidance for assessment is aligned with the assessment purposes. These steps aim to address observed limitations in the case studies (e.g., fragmented service provision, communication silos, or data constraints).

Defining the purpose of the assessment (Step 2) is fundamental for guiding subsequent steps. Several possible purposes (1–7, listed below) are identified. Specific recommendations are outlined in subchapters of Supplementary File S2:

1: Perform an overall resilience assessment of a region for a preliminary evaluation

2: Compare the evolution of resilience between two different years

3: Compare resilience to different hazards

4: Compare how resilience changes when different actions are taken

5: Briefing on the resilience of critical infrastructure (CI)

6: Overall resilience of Natural Areas

7: Briefing to the Decision Support System

A detailed Manual is provided in the ICARIA RAF App for download (top left in Figure 2).

2.5. Contribution to a Decision Support System

Using a resilience assessment as an input to decision-making brings a range of benefits, especially in contexts like public policy, business strategy, infrastructure planning, and risk management. Embedding resilience into decision-making ensures that business operations, growth, and development are sustainable—rather than merely efficient in the short term or narrowly adequate for a particular sector. Including resilience concerns in decision making encourages systemic thinking and helps leaders to see interconnections across systems, to identify synergies (e.g., in data collection, stakeholder engagement, or implementation of multibenefit adaptation actions), and to foster holistic strategies, thus accelerating enhancement.

In ICARIA, a DSS was developed [27], bringing together climate projections, hazard and impact evaluation methods, resilience assessment, and adaptation measures' portfolio, and planning functionalities, into an integrated platform.

The connection between the RAF and the DSS is threefold, with increasing scope: (1) a subset of metrics was integrated into the DSS to provide a holistic resilience snapshot (see Table S5, in Supplementary File S3); (2) an additional layer of information was attached to the most decision-relevant metrics (via the "Additional Info" DSS tag in the RAF App; see

tables in Supplementary File S1); and (3) the predefined overall summary report generated by the RAF App can be exported to the DSS. Guidance is provided in Supplementary File S2.7.

The RAT full assessment is available in the DSS.

2.6. Case Studies

Developing and implementing the assessment process in collaboration with diverse stakeholders empowers them, strengthens their role in decision-making, and encourages their contribution while putting improvement measures into practice. The RAF and RAT frameworks and tools had been used and validated with stakeholders in previous projects [11,12].

One of ICARIA's case studies [19], the Barcelona Metropolitan Area (AMB, from its Catalan acronym) spans 36 municipalities, covering 636 km^2 and over 3.3 million residents. The region faces escalating climate-related threats, including rising temperatures, growing drought periods, and increasingly severe weather events such as storm surges and intense rainfall. These hazards amplify critical impacts, from urban heat islands and heatwaves to devastating floods. While the individual occurrence and consequences of these events are well documented, their combined—and potentially more destructive—effects remain largely unexplored. In this context, ICARIA examined the occurrence and characteristics of compound extreme precipitation and storm surge events. Stakeholders involved were several departments belonging to the Metropolitan Area of Barcelona and the public waste management company TERSA.

Also, an ICARIA case study [19], the Salzburg region covers 7.2 km^2 and is home to 0.6 million people. Located in Austria's Eastern Alps, it is a major tourist destination. It also plays a significant role in Austria's energy production, with relevant hydroelectric power plants. Beyond energy, increasing hazards such as storms, heavy rainfall, river flooding, and landslides also endanger roads and housing infrastructure. In contrast to extreme precipitation, water scarcity is becoming an increasing challenge for Salzburg, impacting energy production and local ecosystems. An operator of critical energy infrastructure was involved in the resilience assessment.

Given the developments in ICARIA resilience methods, prior to the implementation in the case studies, a preliminary version of the platform was accessed by the AMB case study partners and validated, namely regarding its relevance and data availability, detection of inaccuracies, barriers and limitations, and possible improvements [25,26]. Overall, the following was noted:

- Effective articulation is crucial for a regional assessment, where many stakeholders are expected to be involved (concerning several municipalities, with their own independent governing offices).
- Due to the complexity of a regional assessment and the challenges of integrating data from different formats and contexts, it may be important to reduce the number of *essential* metrics.
- Given the diversity of natural areas, it might be adequate to: focus on a subset with similar characteristics and threats (e.g., beaches, urban parks, agricultural fields, or subsurface environments such as mines and caves); or study them separately and then integrate the results.

Data for resilience assessment comes from models, plans, monitoring activities, risk assessment, or city incident records, from various platforms and documents. 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. For confidential purposes, overall results for each resilience objective or capability are presented in the

following section. Supplementary File S4 presents the RAF results at the criterion level. Supplementary File S5 presents ecosystem service metrics' results for each AMB municipality.

3. Results and Discussion on the Application to Case Studies

3.1. Trials for Resilience Assessment

The results of the preliminary application of the frameworks and tools were critically analyzed, leading to modifications in the RAF, regarding metrics' Supplementary Information, city, and service profiles. Stakeholders' opinions were also considered in the revision of the guidelines (previously presented in [20]). They are now available in Supplementary File S2 (from S2.1 to S2.7) and benefit from the application of the case studies.

The application of the RAF framework followed the general procedure illustrated in Figure 5. The pilot application of the RAT was done directly by the stakeholders in the app. Table 1 summarizes the specific Trials made to the case studies.

Table 1. Trials for resilience assessment in AMB and SLR.

Trial	Scope of the Trial	Tool/Procedure	Case Study
1	Holistic resilience assessment of the region, for a given hazard or generic	RAF/Guidelines in Supplementary File S2.1	AMB
2	Holistic resilience assessment of the natural areas in the region	RAF/Guidelines in Supplementary File S2.6	AMB
3	Briefing on resilience of critical infrastructure	RAF/Guidelines in Supplementary File S2.5	AMB
4	Briefing to the DSS	RAF/Guidelines in Supplementary File S2.7	AMB
5	Pilot resilience assessment of critical assets	RAT	SLR

3.2. Holistic Resilience Assessment for Regions and Including Natural Areas (Trials 1 and 2)

AMB implemented both trials 1 and 2 together (Table 1). The holistic resilience assessment of the region (trial 1) was made for a specific hazard (flooding), and the RAF's *organizational* and *spatial* dimensions were addressed with that focus. The holistic resilience assessment of the natural areas (trial 2), specifically developed in ICARIA, was performed for the *functional* and *physical* dimensions of this service. AMB went beyond what was initially planned and also completed the assessment of the *functional* and *physical* dimensions, for mobility in the region—specifically the service for managing and maintaining the Barcelona Ring Roads—and for the solid waste service in one of the municipalities, St. Adria del Besos—namely, for the Integrated Waste Recovery Plant. This facility comprises two plants: the Energy Recovery Plant, operated by TERSA, and the Mechanical–Biological Treatment Plant, operated by Ecoparc del Mediterráneo, providing service to several metropolitan municipalities. It includes bulk waste separation and treatment of separated wood, located at the Municipal Waste Treatment Center of Gavà–Viladecans.

Following the suggestions in the guidelines, AMB moved from the *essential* to *complementary*, and then to the *comprehensive* metrics, for a deeper assessment. For the answers provided, Figure 6 presents an overall assessment of the region and for the organizational and spatial dimensions. It provides the percentage of metrics in each development level (incipient, progressing, or advanced, moving from a lighter to a darker tone; unanswered *essential* metrics in black, not applicable in grey—the unanswered *complementary* and *comprehensive* metrics).

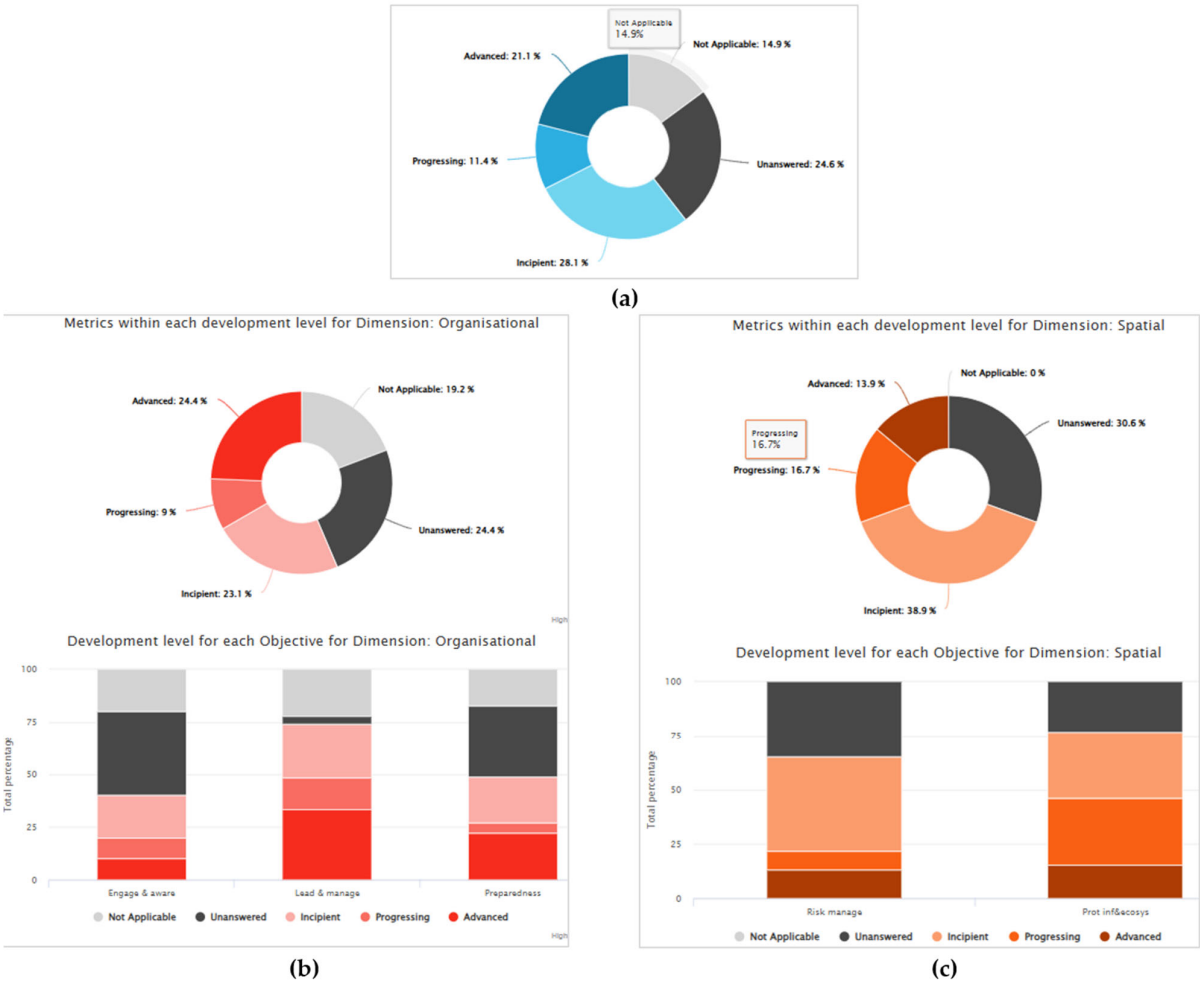


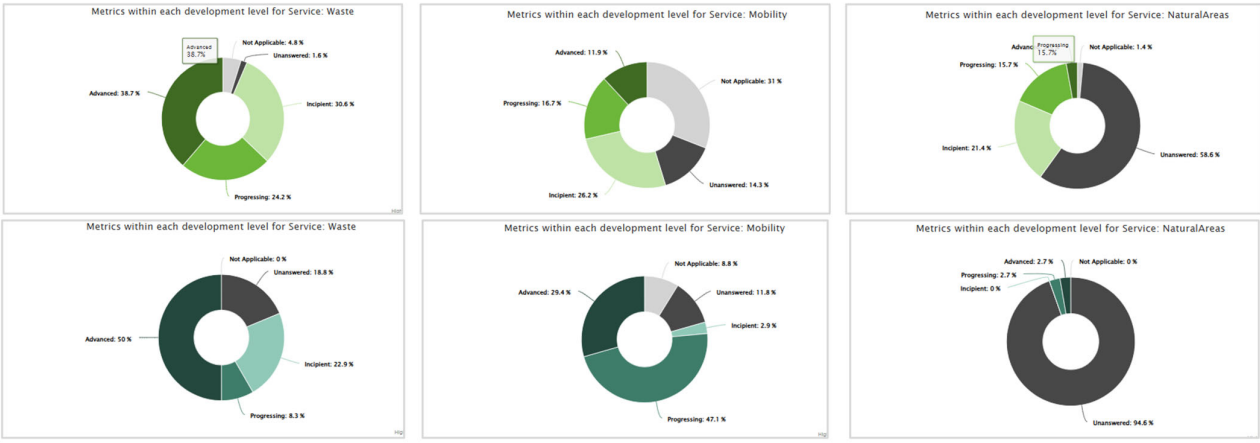
Figure 6. Holistic resilience assessment results for AMB regions (RAF): (**a**) Overall resilience; (**b**) *Organizational* resilience; (**c**) *Spatial* resilience. Global donut charts and resilience objectives' results in bar charts.

Overall (Figure 6a), almost 1/3 of the metrics are in *advanced* or *progressing* levels, demonstrating that the region has already taken relevant and consistent steps towards resilience. Some metrics remain unanswered due to a lack of data, which was expected as AMB moved beyond what was initially planned for this trial.

From the organizational perspective (Figure 6b), the region evidences a significant effort demonstrated by several *advanced* or *progressing* aspects (1/3, mostly *advanced*). It has established strong stakeholder engagement and developed an understanding of cascading effects. An early warning system is in place, along with an emergency operations center and a coordination body. In addition, mitigation targets for greenhouse gases (GHG) have been set. Looking ahead, the region still faces several important challenges. It would benefit from completing a comprehensive hazard assessment and allocating dedicated resilience budgets. Resilience scenarios could be agreed upon, followed by the preparation of a comprehensive resilience plan. Finally, systematic post-event assessments will be required to strengthen future preparedness.

From the *spatial* perspective (Figure 6c), several advanced or progressing aspects were also evident (31%). Hazard maps exist; however, scenarios setting out area-wide exposure and vulnerability from each hazard or multi-hazard do not exist. There is a policy promoting physical measures to enhance resilience in new urban developments, but not so much in peri-urban areas. Protective infrastructure was designed and built according to risk information and is properly maintained.

Figure 7 presents similar information for the *functional* and *physical* dimensions regarding the three services assessed. Further details are provided in Supplementary File S4.



(**a**) (**b**) (**c**)

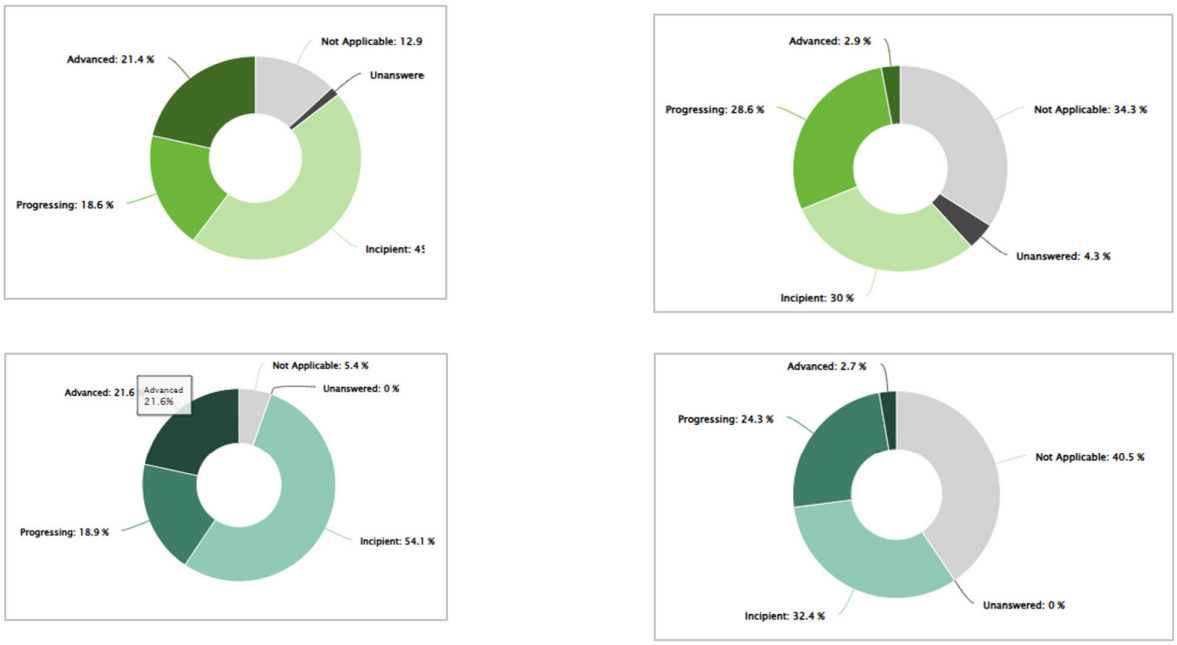
Figure 7. Holistic resilience assessment results for AMB services (RAF): (**a**) Waste (St. Adria del Besos); (**b**) Mobility; (**c**) Natural areas. *Functional* (**above**) and *physical* dimensions (**below**).

When comparing the three services, it becomes clear that Waste and Mobility have improved knowledge on resilience. In fact, on the one hand, this could be expected, as traditionally, the natural areas have not been addressed as a strategic service. On the other hand, it emphasizes the relevance of implementing this change. In both cases, infrastructure resilience (*physical* dimension) is stronger than service resilience (*functional* dimension). It should be noted that the *functional* dimension encompasses, from the utility perspective, several concerns that are included in the *organizational* dimension for the city or regional perspective.

Regarding the Waste service (Figure 7a), a coordination mechanism with other solid waste services is already in place. The service has adequate equipment and staff capacity for normal and emergency circumstances. Infrastructure is maintained on a regular basis, and service interruptions during normal periods are not expected. Critical assets and redundancy options are identified and mapped. However, the infrastructure of the Waste service directly depends on several other services. Waste service would greatly benefit from the implementation of a strategic plan and, even more, from the development of a resilience plan, including also the contributions it might give to the city's resilience. CC is not yet formally integrated into planning, and a significant part of the city is expected to be affected by service interruptions under CC scenarios. Nevertheless, several measures have already been implemented to address both CC mitigation and adaptation.

The region has a strategic plan for Mobility (Figure 7b), although resilience and CC concerns are not included. Critical assets, redundancy options, protective buffers, and cascading effects are mostly identified and mapped. However, the service has some preparedness and autonomy challenges. The population is somehow affected by service interruptions, even though standards and codes are followed, and maintenance is adequately implemented.

For Natural Areas (Figure 7c), however, many metrics remained unanswered. According to AMB, this was because several stakeholders manage different types of natural areas, each with very different realities. Consequently, it was decided to conduct separate assessments for Beaches and Green Areas. The results are presented in Figure 8. Further details are provided in Supplementary File S4.



(a) **(b)**

Figure 8. Holistic resilience assessment results for AMB Natural Areas (RAF): (**a**) Beaches; (**b**) Green areas. *Functional* dimension (**above**) and *physical* dimensions. (**below**).

Even though there is no strategic plan for beaches (Figure 8a), they are assigned to a specific entity, maintenance is in place, there are resilience and CC concerns in planning, and a specific budget for managing beaches. Several ecosystem services are identified in the beaches (they are used for sports, cultural, and recreation activities, and promote biodiversity), although these are not monitored. Although a formal risk assessment has not been conducted, critical assets and protective buffers have been identified. Several impacts are anticipated due to CC, and several measures have been implemented to support adaptation and mitigation.

The green infrastructure (Figure 8b) plan is currently being drafted. Each natural area works in a different manner, regarding finances. The Green Infrastructure Service has a budget for specific actions and programs. Ecosystem services have been identified for most of the areas, and these are mostly used for sports and recreation, among several others. Ecosystem services and the condition of the green areas are not monitored. There is a coordination mechanism in place with other services, e.g., with urban planning and mobility, and community engagement is in place, as plans for natural areas are formally integrated in a participatory process, and design solutions benefit from the community's contributions.

In summary, AMB has a CC Adaptation Plan as well as specific CC adaptation plans for most municipalities, which should be updated with combined risks and action protocols for risk response. This would make the approach both reactive and proactive. In addition, information is still lacking regarding current and future exposure to climate hazards.

For all the municipalities, it was possible to estimate some of the ecosystem services related to green areas, and their contribution to resilience, namely temperature reduction for local climate regulation, air quality improvement, carbon sequestration and storage, and evapotranspiration improvement. With the lack of detailed and accurate data, estimations were based on vegetation size (trees, shrubs, or herbaceous cultures) and green areas size (below 0.25 ha; between 0.25 and 2 ha; between 2 and 8 ha; above 8 ha). The metrics were estimated for all 35 municipalities in the AMB area, for the current situation (Supplementary File S5). Table 2 presents some examples for a few municipalities, with some context information.

Table 2. Ecosystem services metrics related to green areas (estimates). Examples for distinct AMB municipalities. Development level: Advanced (A), Progressing (P), Incipient (I), or null (I_0) (larger grey bars correspond to a higher development level).

Resilience Metrics	Sant Climent de Llobregat		Badalona		Sant Adrià de Besòs	
Temperature reduction for local climate regulation	A	Large green areas, mountainous forest, agriculture	P	Densely populated on the coast, big forest area, scattered parks	I	Coastal old town, densely urbanized
Air quality improvement	A		A		I	
Carbon sequestration and storage	A		P		I_0	
Estimated evapotranspiration improvement	A		A		I_0	

The results show notable differences across AMB's municipalities, indicating where targeted measures could address ecosystem service gaps.

3.3. Briefing on Resilience of Critical Infrastructure and to the DSS (Trials 3 and 4)

From the comprehensive RAF resilience assessment conducted by AMB, a briefing on the resilience of critical infrastructure can be prepared, as recommended in Supplementary File S2.5, Figure 9a illustrates the results obtained for the region and the waste service.

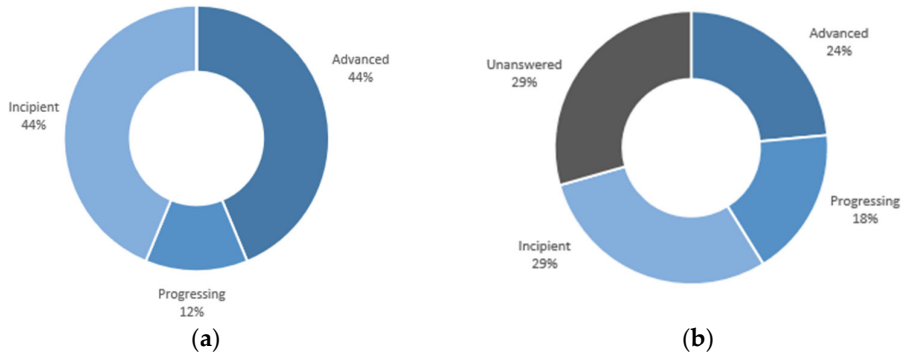


Figure 9. Holistic resilience assessment briefing to (**a**) CI resilience, (**b**) DSS, for AMB.

Critical infrastructure resilience is considered a priority, and corresponding plans or strategies mostly exist for the assessed region, although they are not unique for the whole region, and are actively being implemented. Essential assets for the waste service and beaches have mostly been identified, and those critical to operations are mostly mapped according to hazards and incorporated into risk data. The identification of infrastructure assets supporting mobility in the area is based on established criteria, ensuring that critical transport interfaces are monitored. As a result, the percentage of critical waste and mobility assets out of order last year was minimal, and the average downtime of critical transport interfaces due to infrastructure failures was low.

Under CC scenarios, a significant percentage of sensitive customers are expected to be affected by interruptions in solid waste collection, which is highly dependent on other critical services, as is the mobility service. For Waste, many critical assets, less than 10%, are protected against various hazards under CC scenarios. Regular exchange of information regarding critical infrastructure assets, hazard maps, and risk data with local authorities is lacking. Protective buffers to safeguard assets have not been clearly defined, mapped, or communicated to local authorities. Critical transport interfaces experienced substantial downtime due to flooding-related failures last year. Furthermore, the identification of critical green areas is limited, and the analysis of exposure and service vulnerability for CC scenarios in natural areas is insufficient, yet still, sensitive users are expected to be affected on the beaches.

A briefing for the DSS can be derived based on the full RAF resilience assessment carried out by AMB, as recommended in Supplementary File S2.7 (Figure 9b). This is centered on exposure and known impact for CC scenarios (population, urban footprint, economic activities and natural areas at risk, and service interruptions), protective infrastructure, trends in ecosystem's health, and identification of measures already being implemented in the region or not. Figure 9b illustrates the results obtained for the region and the waste service.

Various measures have been implemented to support CC mitigation and adaptation, including drills and training, stakeholder engagement, improved data collection, and the development of emergency plans. GHG reductions are projected from several assets, such as the fleet, in line with strategic targets. In the Waste service, infrastructural measures include waste separation, a dedicated facility for material recovery, and the use of clean energy

vehicles. In natural areas, interventions focus on strengthening urban–rural connections, establishing green corridors, and linking blue and green areas. NBS are being diversified to enhance ecosystem services, while vegetation is carefully selected to support biodiversity, provide shade, and minimize both water consumption and maintenance needs.

Mobility might experience significant service interruptions under CC scenarios, affecting a high percentage of the area. In the region, several measures to enhance holistic resilience against flooding, heat waves, forest fires, and energy dependence have not yet been mainstreamed by utilities. These include stormwater management solutions, green infrastructure (such as green roofs and expanded outdoor green spaces), renewable energy installations, water reuse and public cooling systems, protective walls, and vegetation management in buffer zones.

3.4. Resilience Assessment of Critical Assets (Trial 5)

The Salzburg region made a pilot implementation of the RAT assessment on their critical energy assets (Figure 10, extracted from the RAT [20]) for various hazards.

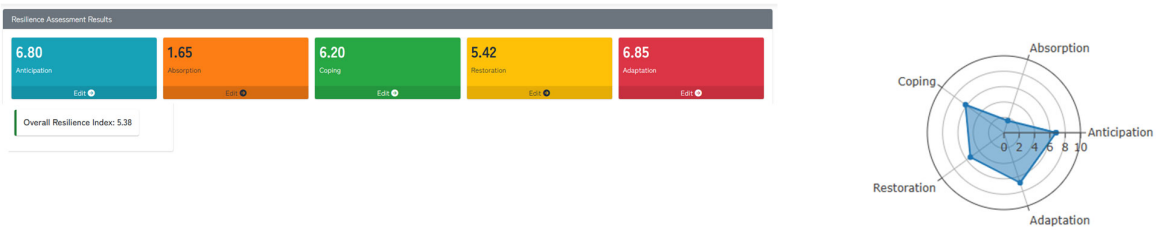


Figure 10. Exploratory resilience assessment of critical energy assets in the Salzburg region (in a 0–10 scale).

The results of this exploratory, data-limited application indicate that the utility performs stronger in anticipation and demonstrates solid capacity for restoration and coping. Yet, absorption seems to be relatively weaker when facing climate-related disruptions. Strong anticipation is particularly relevant, as early awareness and preparedness help to minimize impacts before they occur. Likewise, the ability to adapt and restore services quickly is essential for maintaining continuity and reducing downtime, which could be strengthened. Enhancing coping and absorption capacities will therefore be crucial to ensure the utility can withstand, endure, and recover from increasingly frequent and severe climate pressures.

However, these are preliminary results that do not fully represent the resilience of energy-critical infrastructure in Austria. Some aspects (especially related to absorption) are defined by national law (for instance, with respect to applied standards or the time it takes for backup) and were, therefore, not considered when using the resilience framework.

3.5. Main Advantages and Drawbacks

ICARIA's resilience assessment method delivers a free access framework and a tool to be applied by cities, regions, or services, facilitating visualization of the results of an objective-driven, holistic resilience assessment. It supports decision-making, planning, monitoring of progress, and communication. The emphasis is on regional, city, and critical infrastructure resilience, while social and political dimensions are only addressed when they significantly affect overall resilience. It includes governance, spatial, functional, and operational aspects. The contribution to the economic and health aspects is still incipient. It integrates the interdependencies among sectors and their contribution to the wider urban system or region.

The implementation of the framework requires considerable effort and resources, as it requires contributions from several actors and stakeholders, particularly in cases where there is insufficient collaboration between them, poor availability or quality of data, or limitations in existing information systems. On the other hand, this implementation contributes to improving collaboration among stakeholders and to identifying data gaps and needs for data quality improvement. Although this application relies on a reduced number of case studies, which limits generalizability, it highlights key challenges and can inspire other users to address and overcome these constraints.

In spite of the effort required, there is good evidence that this approach provides an integrated, standardized, and flexible assessment framework that can be successfully used to identify relevant resilience shortcomings, assuring that the measures identified to be implemented are aligned with the resilience objectives of the user, thus contributing to resilience compliance in the mid- and long-term.

4. Conclusions

The ICARIA's resilience assessment method extended existing frameworks and platforms to support structured assessment of urban or regional resilience to CC, both holistically and specifically for critical infrastructure. Following the presented results and discussion of findings, the validation of the frameworks and their apps by the RESCCUE and ICARIA case studies, with different scopes and depths, contributed to a better understanding of their resilience to climate-related events and the actions needed to improve it. This application of the new developments relies on a limited number of case studies with their own context and limitations, which cannot be generalized, so the assessment results should be viewed as an example of what can be accomplished by using the tools, the challenges faced, the data gaps and the support for decision-making, and not so much as their potential replication to similar regions. Given the complexity of implementing a resilience assessment, acknowledged in the case studies, the inclusion of guidelines, together with examples of their application, intends to ensure clarity, consistency, and practical usability.

The application of the ICARIA holistic resilience framework enabled to

- draw attention to the relevance of early identifying the right stakeholders to perform the assessment, assembling a strong and cohesive team, and ensuring they have access to the necessary data and remain engaged throughout the project.
- assess resilience across varying levels of maturity, providing step-by-step guidance while allowing organizations to do more or less, depending on their specific challenges, available data, commitment, and resources.
- identify notable differences across municipalities, indicating where targeted measures could address ecosystem service gaps.
- identify opportunities for improvement, to increase resilience.
- contribute to decision making.
- look at how specific urban services, including natural areas, contribute to making the area resilient to CC.
- facilitate communication between the different stakeholders.

AMB services and regions are now able to identify their strengths and weaknesses, and the levers required to advance to a better state. Given the lack of data on the impact of several CC scenarios, it was not possible to address the uncertainty of the future resilience assessment. Overall, the ICARIA's holistic resilience method proved to be adequate for its purposes. Due to its flexibility, it was tailored to a region, after being applied to a city and its utilities in RESCCUE, to carry out a resilience assessment to CC, monitor

progress, and develop an action plan with this scope and focus, regardless of its level of resilience maturity.

The ICARIA app offers a free, user-friendly way to capture resilience, simplifying metric input, visualizing results through clear graphics, and identifying strengths, gaps, and opportunities for improvement.

The main barriers to the application of the RAF were threefold. First, knowledge is highly dispersed, requiring the involvement of many stakeholders and good coordination at a regional level. Second, a lack of expertise in climate resilience makes certain assessment questions difficult to understand or answer by stakeholders. Third, many experts approach risk management from a reactive perspective rather than a proactive one, making it difficult to embrace the preparedness capabilities. As a result, they often have not yet reflected on the questions posed by the RAF or do not have the necessary data recorded to respond adequately. These aspects were taken into consideration in the development of the guidelines.

The exploratory, data-limited application of the ICARIA RAT enabled a preliminary assessment of the resilience capabilities of the SLR energy critical infrastructure, highlighting the need for further interaction of different governance levels to achieve a complete assessment.

Validation of the ICARIA platform with case studies created valuable opportunities to refine its frameworks and tools, apply and appraise the guidelines, and validate the relevance of its results. Since it is freely available online, the platform holds strong potential for widespread use in the near future. Through its integration with the DSS, the method is expected to guide and empower informed decisions on the most effective actions for building resilience.

The flexibility of the RAF framework allows for the future integration of additional perspectives, such as social or economic dimensions, as well as new objectives, criteria, and metrics related to the services already addressed. They can also be enhanced by incorporating other considerations, such as telecommunications, education, or health, and by accounting for additional hazards or risks, like earthquakes or cyberattacks. These enhancements are encouraged, especially given the platform's user-friendly interface.

Beyond these development opportunities, the platform provides a powerful foundation for advancing academic research on resilience methodologies. Considering the globally recognized challenges of urban and regional resilience amid CC, and the diverse array of potential users, the ICARIA Resilience Assessment Platform is positioned to become an essential tool for regional and city managers, service providers, consultants, academics, and researchers alike.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su18031701/s1. The following supporting information was provided: Supplementary File S1: Objectives, Criteria and Metrics in the RAF; Supplementary File S2: Guidelines for holistic resilience assessment using the RAF App for different purposes; Supplementary File S3: Resilience snapshot in the DSS; Supplementary File S4: Holistic resilience results for AMB; Supplementary File S5: Estimates of some ecosystem services in AMB.

Author Contributions: Conceptualization: R.S.B. and M.A.C.; methodology: R.S.B. and MAC; software: A.M. and A.O.; validation: all; formal analysis: R.S.B. and M.A.C.; investigation: R.S.B. and M.A.C.; resources, all; case studies: A.d.l.C.-C., E.V. and M.B.-B.; writing—original draft preparation: R.S.B. and M.A.C.; writing—review and editing: all; supervision: R.S.B.; project administration: A.d.l.C.-C.; funding acquisition: A.d.l.C.-C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the ICARIA project (Improving ClimAte Resilience of crItical Assets, https://www.icaria-project.eu/ (accessed on 29 January 2026). ICARIA received funding from the European Union's Horizon Europe Research and Innovation program under Grant Agreement nº 101093806.

Data Availability Statement: The ICARIA resilience assessment frameworks are freely available at https://icaria.lnec.pt/ (accessed on 29 January 2026). Data from Case Studies is unavailable due to privacy restrictions.

Acknowledgments: The authors acknowledge the support from ICARIA's AMB case study stakeholders, namely Eugènia Vidal Casanovas (head of the Space Planning Office, Green Infrastructure Service) and Daniel Palacios (head of Beach Service). David Piquer García (Beach Service), María León (head of Environmental Management in TERSA), and Xavier Martínez Arance (Contract for maintenance of the BCN ring roads).

Conflicts of Interest: Author Marianne Bügelmayer-Blaschek was employed by the company Austrian Institute of Technology GMBH. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AMB	Barcelona Metropolitan Area (in Catalan, Area Metropolitana de Barcelona)
CC	Climate Change
CER	Critical Entities Resilience Directive (EU 2022/2557)
CI	Critical Infrastructure
DSS	Decision Support System
EU-Circle	European project, A pan-European framework for strengthening Critical Infrastructure resilience to climate change
GHG	Greenhouse gas
ICARIA	European HE project, Improving ClimAte Resilience of crItical Assets
NBS	Nature-Based Solutions
RAF	Resilience Assessment Framework (for holistic assessment)
RAT	Resilience Assessment Tool (for assessment of critical infrastructure)
RESCCUE	European H2020 project, RESilience to cope with Climate Change in Urban arEas
SLR	Salzburg Region
SSP	Shared Socioeconomic Pathways

References

1. UN-Habitat. *Trends in Urban Resilience 2017*; United Nations Human Settlements Programme: Nairobi, Kenya, 2017; Available online: https://unhabitat.org/trends-in-urban-resilience-2017 (accessed on 3 November 2025).
2. UNDRR. *Disaster Resilience Scorecard for Cities. Preliminary Level Assessment*; United Nations International Strategy for Disaster Reduction; United Nations Office for Disaster Reduction: Geneva, Switzerland, 2017; Available online: https://www.unisdr.org/campaign/resilientcities/assets/toolkit/documents/UNDRR_Disaster%20resilience%20scorecard%20for%20cities_Preliminary_English_Jan2021.pdf (accessed on 3 November 2025).
3. UNDRR. *Disaster Resilience Scorecard for Cities. Detailed Level Assessment*; United Nations International Strategy for Disaster Reduction; United Nations Office for Disaster Reduction: Geneva, Switzerland, 2017; Available online: https://www.unisdr.org/campaign/resilientcities/assets/toolkit/Scorecard/UNDRR_Disaster%20resilience%20%20scorecard%20for%20cities_Detailed_English.pdf (accessed on 3 November 2025).
4. ARUP. *City Resilience Framework. 100 Resilient Cities*; The Rockefeller Foundation, ARUP: New York, NY, USA, 2015; Available online: https://www.rockefellerfoundation.org/wp-content/uploads/100RC-City-Resilience-Framework.pdf (accessed on 3 November 2025).

5. IPCC. *Climate Change 2021: The Physical Science Basis. Contribution of WGI to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2021; 2391p.
6. UNDRR. *Disaster Resilience Scorecard for Cities: Addendum for Gender Equality and Intersectionality*; Guralnick, J., Ed.; United Nations International Strategy for Disaster Reduction; United Nations Office for Disaster Reduction: Geneva, Switzerland, 2024.
7. IPCC. *Climate Change 2023: Synthesis Report. Contribution of WG I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Lee, H., Romero, J., Eds.; IPCC: Geneva, Switzerland, 2023; 184p.
8. European Commission, Directorate-General for Research and Innovation. *Evaluating the Impact of Nature-Based Solutions—A Handbook for Practitioners*; Publications Office of the European Union: Luxembourg, 2021.
9. European Commission, Directorate-General for Environment. *European Water Resilience Strategy*; Publications Office of the European Union: Luxembourg, 2025.
10. Sharifi, A. A critical review of selected tools for assessing community resilience. *Ecol. Indic.* **2016**, *69*, 629–647. [CrossRef]
11. Cardoso, M.A.; Brito, R.S.; Pereira, C.; Gonzalez, A.; Stevens, J.; Telhado, M.J. RAF resilience assessment framework—A tool to support cities' action planning. *Sustainability* **2020**, *12*, 2349. [CrossRef]
12. Katopodis, T.; Sfetsos, A.; Varela, V.; Karozis, S.; Karavokyros, G.; Eftychidis, G.; Gkotsis, I.; Leventakis, G.; Hedel, R.; Koutiva, I. EU-CIRCLE Methodological approach for assessing the resilience of the interconnected critical infrastructures of the virtual city scenario to climate change. *Energetika* **2018**, *64*, 23–31. [CrossRef]
13. Delprato, U.; Cullen, J.; Spielhofer, T.; Del Bianco, D.; Akerkar, R.; Miteva, N.; Gospodinova, Z. *D3.1—RESILOC Resilience Indicators. Resiloc Project, Resilient Europe and Societies by Innovating Local Communities*; Akerkar, R., Ed.; Western Norway Research Institute: Sogddal, Norway, 2022; 139p, Available online: https://www.resilocproject.eu/wp-content/uploads/2022/05/RESILOC_D3.1_V7.0.pdf (accessed on 7 February 2025).
14. Sharifi, A. Urban resilience assessment: Mapping knowledge structure and trends. *Sustainability* **2020**, *12*, 5918. [CrossRef]
15. Medland, C.J.; Chenoweth, J.; Mulheron, M. Infrastructure climate change resilience: A review of resilience assessment frameworks. *Proc. Inst. Civ. Eng. Eng. Sustain.* **2025**, *178*, 344–357. [CrossRef]
16. UN-Habitat. *UN-Habitat City Resilience Profiling Programme. Guide to the City Resilience Profiling Tool*; United Nations Human Settlements Programme: Nairobi, Kenya, 2018; Available online: http://urbanresiliencehub.org/wp-content/uploads/2018/10/CRPT-Guide-Pages-Online.pdf (accessed on 7 February 2025).
17. Cardoso, M.A.; Brito, R.S.; Pereira, C.; David, L.; Almeida, M.C. *Resilience Assessment Framework—RAF. Description and Implementation*; RESCCUE project Deliverable D6.4. 75 p; LNEC: Lisbon, Portugal, 2019.
18. Cardoso, M.A.; Brito, R.S.; Almeida, M.C. Approach to develop a climate change resilience assessment framework. *H2Open J.* **2020**, *3*, 77–88. [CrossRef]
19. Russo, B.; de la Cruz, A.; Leone, M.; Evans, B.; Salgado Brito, R.; Havlik, D.; Bügelmayer-Blaschek, M.; Pacheco, D.; Sfetsos, A. Improving climate resilience of critical assets: The ICARIA Project. *Sustainability* **2023**, *15*, 14090. [CrossRef]
20. Brito, R.S.; Cardoso, M.A.; Sfetsos, A.; Mendes, A.; Matos, R.; Oliveira, A. *Holistic Resilience Methods*; ICARIA project deliverable D3.2. 124 p; LNEC: Lisbon, Portugal, 2024; Available online: https://www.icaria-project.eu/downloads/#deliverables (accessed on 10 November 2025).
21. Turchi, A.; Tedeschi, A.; Leone, M.; Gregorio, D.; Zuccaro, G.; Coronas, A.; Bügelmayer, M.; Zarikos, I. *ICARIA Holistic Modelling Framework*; ICARIA project Deliverable D1.1; UNINA: Napoli, Italy, 2023; Available online: https://www.icaria-project.eu/downloads/#deliverables (accessed on 7 February 2025).
22. Brito, R.S.; Cardoso, M.A.; Cruz-Coronas, A.; Leone, M.; Turchi, A.; Tedeschi, A.; Molina-Lopez, P. Blueprint for evaluating the climate resilience of natural areas. *Blue-Green Syst.* **2025**, *7*, 323–337. [CrossRef]
23. *ISO 9001:2015*; Quality Management Systems—Requirements. International Organization for Standardization (ISO): Geneva, Switzerland, 2015.
24. TEEB. *TEEB Manual for Cities: Ecosystem Services in Urban Management*; The Economics of Ecosystems and Biodiversity (TEEB); United Nations Environment Programme: Geneva, Switzerland, 2011.
25. Cruz, A.; Molina, P.; Zarikos, I.; Buegelmayer, M.; Lavasa, A. *WP3 Testing Results*; ICARIA project deliverable D3.6; AQUATEC: Barcelona, Spain, 2024; Available online: https://www.icaria-project.eu/downloads/#deliverables (accessed on 12 September 2025).

26. Brito, R.S.; Cardoso, M.A.; Molina, P.; Cruz, A.; Veza, E.; Russo, B. Resilience assessment of the natural areas in the Barcelona Metropolitan Area. In Proceedings of the International Conference on Nature-Based Solutions for Water Management and Climate Adaptation, Belgrade, Serbia, 3–5 July 2024.
27. Lavasa, A.; Konstantinidis, I.; Tzivaras, V.; Arvanitidi, A.; Moumtzidou, A.; Gialampoukidis, I. *Decision Support System V1*; ICARIA project deliverable D3.4; DRAXIS: Athens, Greece, 2025; Available online: https://www.icaria-project.eu/downloads/#deliverables (accessed on 2 December 2025).

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