Mapping Territorial Vulnerability for Resilience Planning. The R3C-GeoResilience Tool Applied to the Union of Bassa Romagna (Italy)

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Article

Mapping Territorial Vulnerability for Resilience Planning. The R3C-GeoResilience Tool Applied to the Union of Bassa Romagna (Italy)

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Abstract

In contemporary spatial planning, territorial resilience is rapidly gaining relevance, referring to a territory's capacity to withstand, adapt to, recover from, and transform in response to environmental, social, and economic pressures. However, several constraints limit its operationalisation in planning. A key element to addressing this gap is to investigate where and which interventions are most urgently needed to tackle the impact of hazards on territories. This can be achieved by understanding and localising the vulnerabilities of territorial systems, thereby enabling the definition of appropriate mitigation and adaptation measures. This paper presents the application of R3C-GeoResilience, an open-source GIS tool and its methodological framework, which allows mapping territorial vulnerabilities across different geographical contexts and spatial scales. The methodology is applied to the Italian case of the Union of Bassa Romagna (UBR), aiming to build capacity for local practitioners to implement resilience thinking in decision-making processes. Findings underscore the potential of R3C-GeoResilience to enhance evidence-based planning and policymaking, supporting adaptive and transformative strategies to address territorial vulnerabilities. The application of the research demonstrates the replicability and adaptability of the methodological framework for integrating participatory vulnerability mapping into local governance and urban planning strategies, thereby enhancing the resilience of territories.

Keywords: urban resilience; vulnerability; Geographic Information System (GIS); urban planning; R3C-GeoResilience

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1. Introduction

Contemporary cities are navigating a landscape marked by unprecedented uncertainty, complexity, and unpredictability. In this context, resilience is increasingly prescribed—both in academia and policy arenas—as a toolkit for addressing crises, particularly in dealing with the systemic challenges of cities. Recent advancements in resilience thinking reflect a paradigmatic shift: moving away from a static, equilibrium-based understanding of resilience, which promotes bouncing back to normality, toward a more dynamic perspective that emphasises the capacity to adapt, transform, and even flourish. This reconceptualisation happens in line with a broader paradigm shift that views the world as complex, non-linear, and constantly evolving, rather than as orderly, mechanical, and predictable. In this context, the frameworks of social-ecological resilience [1], evolutionary resilience [2,3] and co-evolutionary resilience [4] have emerged as important contributions to this evolving theoretical landscape.

Yet, this conceptual innovation has not been adequately matched by operational effectiveness through context-specific actions for enhancing resilience in cities. This gap stems from several limitations, including the lack of robust methodologies for identifying meaningful measures of resilience that consider the spatial dimension and the geographical distribution of factors affecting resilience. At present, several valuable frameworks exist that analyse resilience or vulnerability in different ways. For example, the JRC Resilience Dashboards define indicators of capacities and vulnerabilities to evaluate resilience as the ability to advance toward policy objectives [5]. The Building Resilient Neighbourhoods initiative identifies key community aspects that contribute to neighbourhood resilience and offers a checklist for analysis [6]. MCR2030 proposes a three-stage 'resilience roadmap' to guide cities in enhancing resilience over time [7]. Alongside these global frameworks, sector-specific and hazard-specific methodologies have also advanced. For example, recent studies have developed quantitative, index-based methods for assessing the seismic resilience, either through comprehensive reviews [8] or through novel multi-index assessment frameworks that integrate uncertainty modelling [9]. These works illustrate the growing trend of applying resilience thinking in different disciplines, though they are oriented toward engineering applications in the infrastructure sector. Our research aims to extend resilience thinking beyond infrastructure systems to governance and territorial planning. In other words, while existing works provide valuable insights into resilience within specific sectors, there remains a lack of approaches that can analyse cross-sectoral territorial vulnerabilities and directly support resilience planning at the local level.

Another research gap concerns the multi-hazard perspective adopted in this study. Existing approaches often fail to account for the complexity and interconnectedness of negative trends, systemic disruptions, and hazards that simultaneously influence territorial systems. More specifically, the increasing frequency and severity of natural and human-induced disasters, alongside widening inequalities, fractured social fabrics, and escalating geopolitical tensions, are co-evolving and mutually reinforcing each other, creating a complex web of systemic vulnerability. While these challenges are deeply interconnected, policy responses often remain fragmented and siloed. Even when such disruptions occur at different points in time, they are usually systemically linked, with the potential to reproduce or intensify one another.

To address these scientific challenges, it is essential to identify which dimensions of the urban or territorial system can be spatially measured, thereby supporting policymakers and planners in building preparedness capacities. This is crucial for designing interventions that not only prevent undesirable trends and catastrophic events but also enable structural transformations that strengthen long-term resilience. Vulnerability provides the analytical entry point for understanding where and how systems are most at risk, offering the necessary basis for targeted, context-specific resilience strategies. To be more specific, vulnerability is one of the three dimensions of risk, together with exposure and hazard. Vulnerability can be defined as the propensity or predisposition to be adversely affected and the lack of capacity to cope and adapt [10]. More specifically, it represents the likelihood that assets will be damaged when exposed to a hazard [11]. Vulnerability encompasses "the conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards" [12]. The degree of vulnerability of a territorial system directly influences its resilience, making it essential to adopt targeted adaptation measures to enhance its response and transformation capacities [4].

This research presents a methodological approach and a place-based vulnerability mapping plugin in QGIS, called R3C-GeoResilience, which leverages the expertise of local practitioners and addresses the complexity and interconnectedness of environmental, infrastructural, and socio-economic factors. By moving beyond fragmented and reactive responses, the tool enables more anticipatory and proactive planning through a multi-risk analysis. The plugin is introduced as a means to operationalise this conceptual framework and support institutions in designing place-based pathways toward territorial resilience [13]. R3C-GeoResilience translates mainstream frameworks into an operational, place-based method that can support planning. UNDRR and IPCC provide conceptual risk framings, and the JRC Resilience Dashboards monitor vulnerability and coping capacity indicators at national/regional scales. However, neither specifies how to produce fine-grained, GIS-based vulnerability maps. By contrast, R3C-GeoResilience (i) works at local resolution (500 $\times$ 500 m grid, defined by data availability and adaptable to higher-resolution inputs), (ii) integrates both trend- and event-type hazards with territorial conditions via a participatory correlation-matrix weighting, (iii) computes a single, compound vulnerability index through map overlay operations, and (iv) embeds the whole workflow in an open-source QGIS plugin. While JRC dashboards report separate resilience indicators categorised into key dimensions, R3C-GeoResilience approach synthesises them into cumulative, spatially explicit vulnerability maps that directly support the selection and prioritisation of adaptation and mitigation actions within local governance.

To test and validate the tool, the Union of Bassa Romagna (UBR) is selected as the case study for the vulnerability analysis. UBR is a public body established in 2008 to coordinate territorial governance and improve service delivery across nine municipalities. Located in the heart of the province of Ravenna, about 40 km from the Adriatic Sea, the UBR lies within the vast alluvial plains that extend toward the Romagna hills. Its strategic position ensures relatively good accessibility, benefiting from proximity to key regional economic hubs such as Bologna and other centres along the Via Emilia, as well as connection to the E55 highway. Despite its modest population size, of around 100,000 inhabitants, the UBR plays a crucial role in regional governance. Among its municipalities, Lugo is the most populous municipality, with 31,854 residents, while Bagnara di Romagna is the smallest, with 2425 inhabitants [14]. The area's landscape has been historically shaped by an extensive network of canals and wetlands, reinforcing its strong agricultural identity. However, its geomorphological characteristics, situated between the hills and the Adriatic Sea, make it particularly vulnerable to extreme weather events, most notably—but not limited to—flooding and hydraulic risk, which frequently generate environmental, economic, and social disruptions. The UBR is selected as the case study since it presents features that are common across many European and Mediterranean territories: recurrent exposure to floods, a mixed agricultural–urban land use structure, and governance arrangements that rely on multi-level coordination and inter-municipal cooperation. These characteristics make the case study both relevant locally and also representative of typical challenges faced by medium-sized territories across Europe, thereby supporting the transferability of the proposed tool.

As shown in Figure 1, more than 45 per cent of the Emilia-Romagna Region is exposed to low- and medium-probability hazards (LPH and MPH), while over 10 per cent of the

Region is exposed to high-probability hazards (HPH). This makes the Region rank first among Italian regions in terms of exposure to flood risk [15]. In recent years, the region has faced increasingly severe flooding events, particularly in May 2023 and September 2024, when extreme meteorological phenomena caused widespread devastation in large portions of Romagna. These crises have underscored the need to reassess the governance model of the UBR, using its multi-municipal structure to develop coordinated strategies for disaster resilience. The declared goal is to develop long-term adaptation solutions that address the challenges of a shared governance system. Currently, the UBR manages 29 municipal services, with key investments in social welfare, environmental management, urban planning, and security, ensuring strong institutional support and proximity to citizens. Moreover, the UBR plays a fundamental role in coordinating Civil Protection efforts: while operational responsibilities remain with individual mayors, strategic disaster management is handled by UBR-appointed officials. In this sense, the UBR not only acts as an implementer but also as an intermediary between global climate policy frameworks and local realities. It helps translate high-level strategies into context-sensitive actions that respond to the specific vulnerabilities and capacities of the territory, demonstrating its key role in the multi-level governance structure of the area. Within this framework, the UBR is also developing its General Urban Plan, which incorporates measures to enhance territorial development and improve resilience. Recognising the growing challenges posed by climate change, the capacity building initiative *VALUE4UCBR* has been launched, which aims to equip public administrators and technical professionals with the tools and knowledge necessary to address territorial vulnerabilities and enhance disaster preparedness and long-term resilience. This is part of an effort to foster collaborative governance and strengthen institutional capacity, enabling UBR to turn existing challenges into opportunities and ensure a more resilient and sustainable future for the region.

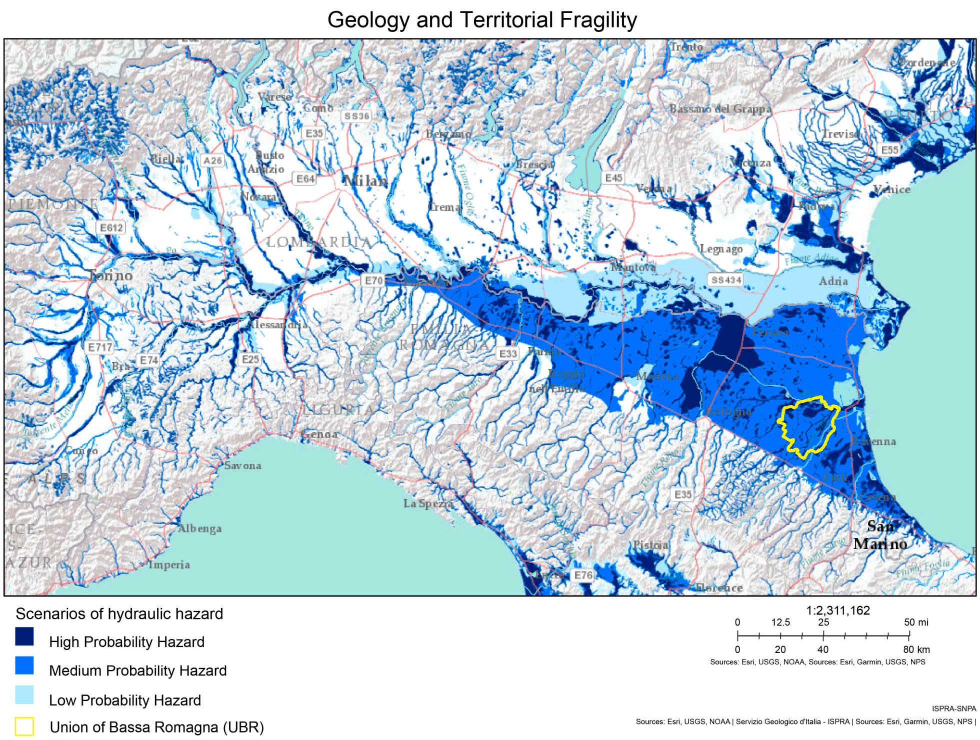


Figure 1. Map of areas potentially subject to flooding under different probability scenarios, based on flood hazard maps prepared by the River Basin District Authorities [15]. Map edited by the authors.

The initiative has delivered three different capacity-building activities. The first action concerned information and training. This phase was dedicated to the theoretical and conceptual foundation of resilience. Public officials and administrators were trained through expert-led seminars and online sessions, equipping them with up-to-date knowledge on resilience strategies and best practices. This was followed by the implementation of the territorial resilience lab where technical professionals engaged in hands-on workshops to test and apply vulnerability analysis methodologies using the R3C-GeoResilience tool. Participants gained practical insights into data collection, scenario development, and resilience analysis frameworks, while simultaneously applying GIS-based mapping to assess territorial vulnerabilities. The initiative lays the foundation for analysing the territorial vulnerabilities and subsequently facilitates informed decision-making, effective risk management, and sustainable urban planning by equipping policymakers and local practitioners with the necessary skills and analytical tools.

To guide this study, we here raise an overarching research question: How can a place-based, open-source, and participatory tool support local administrations in mapping territorial vulnerabilities and translating them into actionable strategies for resilience planning? This question is complemented by three relevant sub-questions on how to (i) integrate multiple hazards into a compound vulnerability index, (ii) assess the added value of participatory weighting, and (iii) explore the transferability of the approach to other geographical and administrative contexts.

The following sections will first present the methodological approach and a detailed explanation of the GIS tool. Subsequently, the role of the training program and the capacity-building workshop with local practitioners in refining the research will be discussed. The paper concludes with the presentation of the main results and key insights emerging from the study.

2. Materials and Methods

The methodology adopts two key international frameworks, both of which conceptualise risk as a compound factor. First, according to the United Nations Office for Disaster Risk Reduction (UNDRR) [12], to improve understanding of disaster risk, it is necessary to break it down into three dimensions: exposure, vulnerability, and hazard characteristics. Vulnerability, as one of the three risk dimensions, is defined as "the conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards". In the same vein, the Intergovernmental Panel on Climate Change—IPCC [10], clarifies that "risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards." This threefold conceptualisation of risk and the definition of each dimension are represented in Table 1.

Among these three dimensions of risk, we focus on vulnerability as the object of study and measurement. To measure vulnerability, two fundamental questions must be answered: first, vulnerability of what, and second, vulnerability to what. To address the question of vulnerability of what, we refer to the territorial system's physical, socio-economic, and environmental characteristics (the system's conditions), and to address the question of vulnerability to what, we consider the impacts of the hazard (either trends or events).

In other words, analysing vulnerabilities of territorial systems requires an integrated perspective on both system conditions and hazards. Conditions refer to the inherent characteristics of a territorial system that influence its susceptibility to disturbances. These include physical, social, and environmental attributes—such as demographic composition, land use, soil consumption, the quality of the built environment and building stock, and the state of infrastructure—which together define the system's baseline fragility. These conditions then need to be correlated with the short-term and long-term hazards, which encompass trends and events that can stress or disrupt the system. Trends act as gradual stressors, such as economic decline, rapid urbanisation, natural and built environmental degradation, and increasing energy demand due to climate change [16], while events refer to sudden shocks like earthquakes, floods, or extreme weather events.

Table 1. Threefold conceptualisation of risk and the definition of each dimension [10,12].

Concept	Definition
Risk F (Hazard, Exposure, Vulnerability)	The **potential for adverse consequences** for human or ecological systems, recognising the diversity of values and objectives associated with such systems. risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards.
Hazard	The **potential occurrence** of a natural or human-induced physical **event or trend** or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources.
Exposure	The **presence** of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in **places and settings that could be adversely affected.**
Vulnerability	The **conditions** determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards

The tool operationalises this framework to calculate composite vulnerability indexes by first mapping all indicators and then evaluating the interplay between the indicators of system's conditions and hazards through a matrix-based weighting system (hereafter referred to as the correlation matrix). To achieve the latter, indicators referring to conditions of the system are systematically linked to trends and events, enabling the quantification of their cumulative impact [13]. Table 2 represents a prototype of the correlation matrix, which, in the first two columns, presents the conditions of the system divided into three components that define the fundamental characteristics of a territory, which are influential on its vulnerability. These components include (A) natural environment & landscape; (B) built environment, cultural heritage & infrastructure; and (C) economy & society. In addition, the hazards to which vulnerability is analysed are divided into trends and events.

Table 2. The prototype of the correlation matrix, which correlates the indicators representing the conditions of the territorial systems with those of hazards (both trends and events).

Components	Conditions of the System	Hazards						
		Trends			Events			
		T1	T2	T3	E1	E2	E3	E4
A: Natural environment & landscape	A1							
	A2							
B: Built environment, cultural heritage & infrastructure	B1							
	B2							
	B3							
C: Economy & Society	C1							
	C2							

The correlation matrix serves as a weighting mechanism, enabling the consideration of expert assessments to assign relative importance to the intersections between condition indicators (the rows) and hazard indicators (the columns). These weights are based on an ordinal scale, where experts evaluate the strength of the relationship as none, weak, strong, or very strong, corresponding to the values 0, 1, 2, and 3, respectively. In other words, experts assess the extent to which the system conditions represented by each indicator may influence—positively or negatively—the territorial resilience in response to each trend or event. For each indicator—whether related to conditions or hazards—a GIS representation is provided using 500 × 500 m geographical units. This resolution is chosen as a balance between policy relevance and data availability. This scale corresponds to the level at which many official Italian and European datasets (e.g., census, land cover, hazard maps) are provided and is fine-grained enough to capture intra-municipal variability, while remaining computationally manageable and consistent across indicators.

These maps, on one hand, and the weights from the correlation matrix, on the other, are then integrated using the spatial overlay technique to generate the vulnerability index. More specifically, for each geographical unit or map cell, the vulnerability index is calculated by summing the products of all possible pairs of condition and hazard indicator values, each multiplied by the corresponding weight from the correlation matrix. Below in Table 2, we present a prototype of the correlation matrix, which follows the mathematical framework for estimating the vulnerability index. It is important to note that, like any other composite index, the R3C-GeoResilience vulnerability index represents a simplification of complex territorial dynamics and should therefore be used with caution, ideally alongside complementary expert knowledge that examines specific territorial conditions in greater detail. Our experience in the UBR workshops with practitioners from various sectors confirmed the value of their insights in contextualising the results and maximising the tool's effectiveness.

For each geographical unit, the calculation of the vulnerability index is based on the matrix $C = \{c_{jk}\}$ reporting the correlations between the j-th condition of the system and the k-th hazard, created with the collaboration of the experts, and a double matrix $(D_1, D_2) = \{(d_{ij}, d_{ik})\}$ reporting on each i-th row, the values of the single indicators found on the specific geographical unit.

More specifically, each component c_{jk} of the C matrix describes the relationship existing between the j-th condition and the k-th hazard (trend or event), and takes on a greater value the stronger this relationship is, i.e., the greater the impact of the occurrence of events linked to this hazard on the susceptible factors that may be present on the territory (according to the evaluations made by the experts).

On the other hand, each component d_{ij} of the D_1 matrix represents the value of the j-th condition indicator on the i-th geographic unit, while each component d_{ik} of the D_2 matrix represents the value of the k-th hazard indicator on the i-th geographic unit.

The overall vulnerability index on the i-th geographic unit is then calculated as a weighted average of the products of all possible pairs of conditions and hazards (be they trends and events), using the c_{jk} "correlations" as the weight of each product. In formula, the overall vulnerability index I_i for the i-th geographical unit is obtained as the double sum.

$$I_i = \frac{1}{n * m} \sum_{j=1}^{n} \sum_{k=1}^{m} d_{ij} d_{ik}\, c_{jk},$$

where n is the number of indicators representing the conditions of the system and m is the number of hazards considered. Note that the value of this double sum is divided by the product between the number of conditions and the number of hazards to normalise the index, i.e., to obtain a quantity that takes values in [0, 1] (being obtained as the sum of n times m summands).

Constants a_j and b_k, with values in [0, 1], are then added to the above formula to allow the user to give greater weight, or relevance, to individual indicators of conditions or trends or events, obtaining the expression:

$$I_i = \frac{1}{n * m} \sum_{j=1}^{n} \sum_{k=1}^{m} d_{ij} d_{ik}\, c_{jk}\, a_j\, b_{k.}$$

This final formula allows, for example, by setting $a_j = 0$, the j-th indicator referring to the conditions of the system to be removed from the model and thus from the calculation of the final value of the index. Similarly, by setting $b_k = 0$ the k-th hazard is removed from the model. The choice of these weighting values is made by the user with scrollbars, thus enabling more specific vulnerability indices to be obtained at a glance, focusing on particular components (A, B, or C) or specific trends or events present in the territory.

Building on the mathematical framework, the QGIS plugin (Figure 2) operationalises the vulnerability assessment in a user-friendly and flexible environment. It allows users to define and update spatial indicators based on local conditions, integrate new data, and visualise vulnerability maps. The plugin was developed using Python 3.12, a programming language that is also widely used and well-documented, and it employs the open-source Qt Creator libraries for user interface control, as an integrated development environment (IDE) that enables developers to create cross-platfo rm applications. Users can specify, via an Excel file, the number and codes of indicators referring to the conditions of the system, grouped into three categories with a maximum of nine per category. Similarly, it is possible to indicate the trends and events which are significant for a given territory. Aligned with the methodology outlined above, the plugin employs the correlation matrix and enables users to interact with individual components, allowing for optimal visual customisation through selectable colour palettes and adjustable transparency levels. In addition, leveraging QGIS functionalities, it is also possible to visualise and integrate geo-referenced data either at the local scale or through network services such as Web Map Service (WMS), Web Feature Service (WFS), and similar protocols. Within this framework, vulnerability maps can be overlaid with information of different types -such as updated datasets, orthophotos, urban planning instruments, cadastral data, and more- thus supporting the planning and decision-making process.

The methodological design explained here builds on the broader family of GIS-based decision-making and decision-support tools, where geographical data are combined with value judgments to support spatial decision-making [17], for example, through approaches such as weighted linear combination and the analytic hierarchy process (AHP). It also relates to other indicator-based spatial planning methodologies that use cartographic outputs to inform decision-making [18]. Our contribution extends these approaches by embedding the correlation matrix and participatory weighting process into an open-source QGIS plugin and ensuring both methodological transparency and operational replicability. More detailed, as illustrated in the previous section, vulnerability is a place-based concept that, when it comes to its measurement, requires flexibility in the selection and application of spatial indicators. In this context, the plugin proves particularly effective, as it allows both the flexibility to define new indicators for each component based on the specific characteristics of the territory and the capacity to enable continuous updates of the spatial indicators being monitored. New indicators can be easily introduced and inserted in place of the old ones if new data becomes available or scientific advancements are made in the field, leading to more solid and holistic indicators. Additionally, the plugin's flexibility enables the timely integration of new data as soon as it becomes available.

The development of the plugin was not only a technical endeavour but also a key component of a broader participatory process aimed at embedding the tool within real-world planning practices. To ensure its effective application and local relevance, the plugin and its methodological framework were tested and validated through a dedicated training program and capacity-building workshop with local practitioners. The following paragraphs outline the structure and implementation of this process within the capacity-building initiative, highlighting the active involvement of public officials in refining indicators, applying the tool, and shaping locally relevant adaptation strategies.

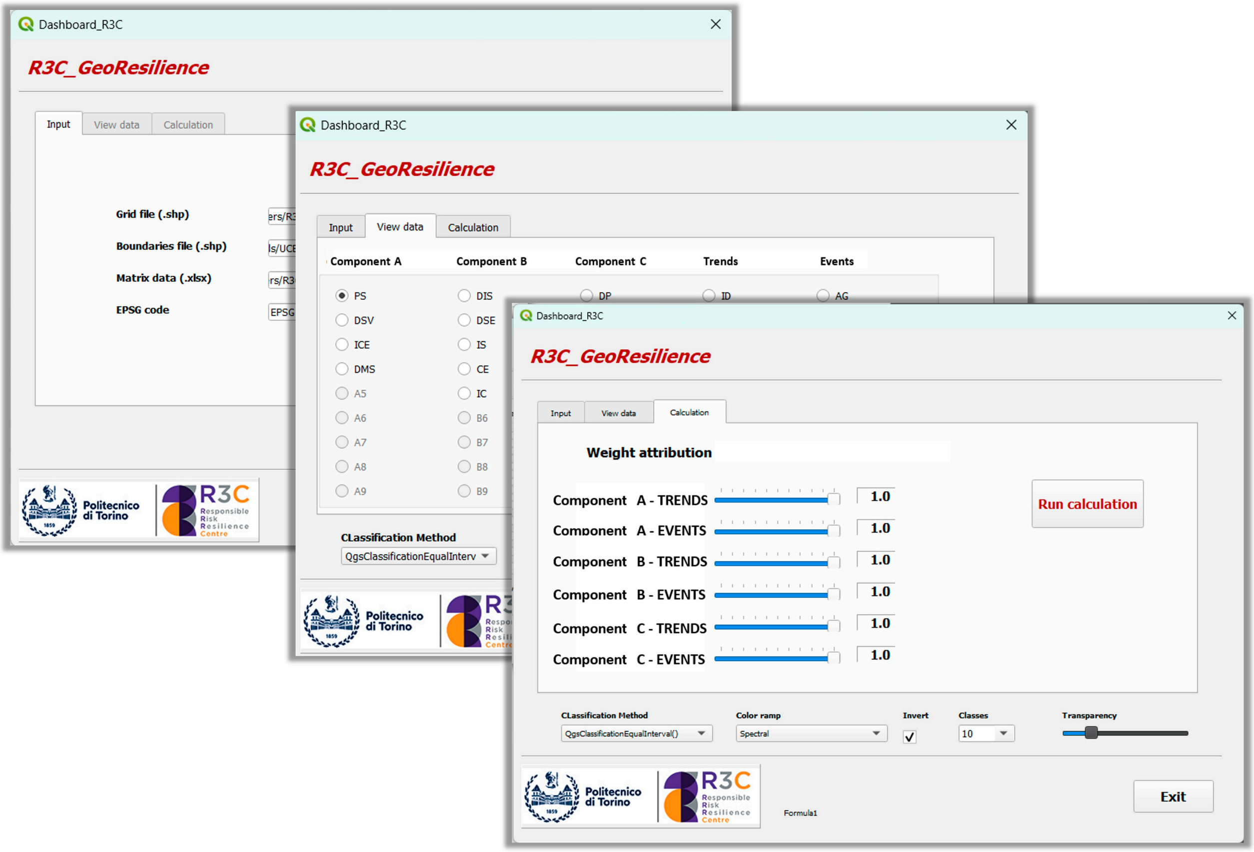


Figure 2. Visualisation of the three main tabs of the R3C GeoResilience Plugin. From top to bottom: the first tab is used to insert input data; the second tab allows visualisation of individual maps representing each component of the system's conditions, trends, and events; the third tab displays the final vulnerability map after clicking the 'Run Calculation' button.

The involvement of local practitioners was an integral component of the research conducted within the *VALUE4UCBR*. This involvement had two main objectives: first, to engage local practitioners in selecting the most representative indicators for a context-based analysis of vulnerability; and second, to inform and train public officials and administrators of the UBR on territorial resilience by providing both theoretical foundations and practical strategies to support decision-making. This is also relevant regarding the reliance of the methodology on expert judgement. The weighting of indicators can be influenced by subjectivity, by the specific composition of the expert group, and by different levels of technical knowledge and capacities. However, in this study, such risks were mitigated through the training program, which provided both online courses and in-person workshops to enhance the skills of local practitioners and foster a shared understanding of the methodology, indicators, and key concepts. This capacity-building component helped mitigate biases and supported a more consistent and informed participatory process.

Therefore, local practitioners actively contributed to the selection of indicators. The indicators employed in this analysis were defined during a preliminary phase of desk research, where the availability of data was also considered, and subsequently supported by feedback from UBR local practitioners to verify their local relevance. The spatial data were extracted from open-access GIS dataset sources [19–30] or provided directly by the UBR. The finalised indicators were systematically structured, in accordance with the established methodological framework, into the three dimensions: the conditions of the systems, trends, and events. The following step, an in-person workshop, played a pivotal role in refining the methodological approach, facilitating the validation and further calibration of the indicators through several feedback sessions with local practitioners of UBR. The outcome of this iterative process is a finalised set of indicators, presented in Table 3. A detailed breakdown of these categories and their associated indicators, along with the source of the spatial data used to calculate the indicators, is presented in Table S1. In addition, the maps related to each indicator are presented in Figures S1–S25 in the Supplementary Material.

Table 3. List of the indicators defined and calculated regarding the three components of the system's conditions, trends, and events.

Conditions of the System						**Hazards**			
COMPONENT A: Natural Environment & Landscape		**COMPONENT B: Built Environment, Cultural Heritage & Infrastructure**		**COMPONENT C: Economy & Society**		**Trends**		**Events**	
A1	Permeable Land Surface Index (PLSI)	B1	Weighted Road Network Density Index (WRNDI)	C1	Residential Population Density Index (RPDI)	T1	Structural Dependency Index (SDI)	E1	Historical Flood Frequency Index (HFFI)
A2	Weighted Green Infrastructure Availability Index (WGIAI)	B2	Educational Services Density Index (ESDI)	C2	Elderly Population Ratio (EPR)	T2	Migration Dynamics Index (MDI)	E2	Inundation Hazard Level Index (IHLI)
A3	Cycling Infrastructure Density Index (CIDI)	B3	Healthcare Facility Density Index (HFDI)	C3	Foreign Resident Incidence Index (FRII)	T3	Land Consumption Change Index (LCCI)	E3	Bioclimatic Stress Index (BSI)
		B4	Building construction characteristics (BCC)	C4	Economic Activity Density Index (EADI)	T4	Aging Dynamics Index (ADI)	E4	Seismic Liquefaction Risk Index (SLRI)
		B5	Cultural Heritage Sites Density Index (CHSDI)	C5	Active Population Employment Rate (APER)	T5	Chronic Air Pollution Exposure Index (CAPEI)	E5	Industrial Accident Risk Index (IARI)
				C6	Territorial Property Value Index (TPVI)			E6	Short-Term Air Pollution Exposure Index (STAPEI)

Additionally, local practitioners of UBR received training designed to enhance their capacity for resilience-oriented decision-making. The training was structured into two phases: an initial series of theoretical and technical lectures followed by a hands-on workshop. The first phase consisted of four online sessions, which introduced key concepts and methodologies for measuring and mapping vulnerabilities, and also presented the methodology and the QGIS tool. The sessions covered several themes, including resilience in spatial planning, the analysis of territorial vulnerabilities, and the methodological approach developed for mapping these vulnerabilities. The second phase consisted of an in-person workshop held over two days, designed to translate theoretical knowledge into practice, as shown in Figure 3. During the workshop, an overview of the methodology was provided, and each spatial indicator was presented and discussed. The participants' feedback was collected in real-time using the MIRO platform, enabling the final selection and refinement of the indicators inserted into the plugin, which were used to calculate and map the vulnerability index. Following this, the Excel-based correlation matrix was shared with every participant, and they individually attributed the relationship values between the indicators as explained in the methodology section. This process played a crucial role in refining the vulnerability analysis by integrating expert knowledge with local insights. By inserting the indicators and the outcome of the correlation matrix filled out by the participants, overall vulnerability maps were generated in real-time and presented.

Figure 3. Interactive workshop in UBR session where local practitioners refined territorial indicators through collaborative tools and their local expertise, and where they weighted the correlation matrix.

Following the workshop, a final online session was held to present and discuss the outcomes of the experimental phase. The key objective was to translate the insights gained from the vulnerability analysis into actionable strategies for mitigation and adaptation, which will be explained in Section 3.

3. Results and Discussions

During the workshop, each participant was asked to complete the vulnerability correlation matrix independently, assigning values from 0 to 3 to reflect the relationship between system condition indicators and hazard indicators (trends and events). This approach allowed each participant to weigh indicator importance according to their own expertise. Once all individual matrices were completed, a final summary matrix (as shown in Table 4) was generated by averaging the values assigned by each participant and normalising them. By incorporating local knowledge, the weighting exercise ensured that the most relevant factors influencing vulnerability were emphasised, aligning the analysis with the actual dynamics of the territory. The final weighting, therefore, represents a balanced synthesis of local knowledge, contributing to a more context-sensitive and locally grounded vulnerability analysis.

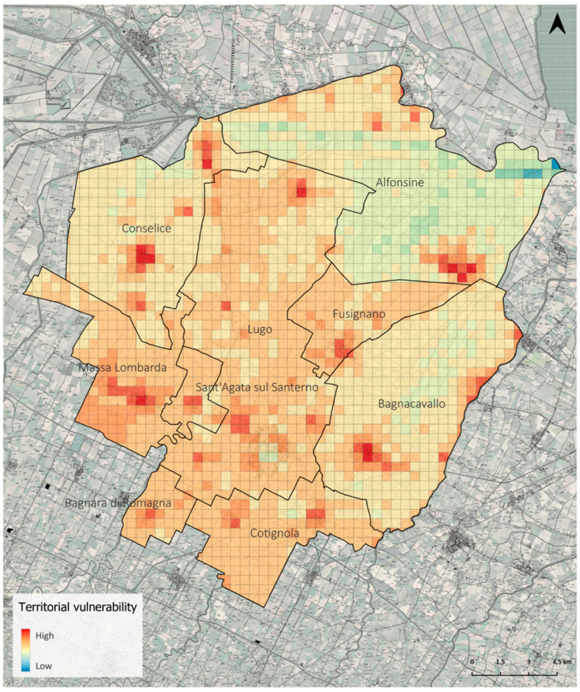
Table 4. Vulnerability correlation matrix representing the normalised values of the average evaluation of the local practitioner during the workshop. Darker colour represents higher value of correlation. For the full name of the indicators, look at Table 3.

			TRENDS					EVENTS					
			SDI	MDI	LCCI	ADI	CAPEI	HFFI	IHLI	BSI	SLRI	IARI	STAPEI
CONDITIONS OF THE SYSTEM	COMPONENT A: Natural Environment & Landscape	PLSI	0.00	0.00	0.78	0.15	0.42	1.00	0.96	0.89	0.67	0.63	0.50
		WGIAI	0.41	0.26	0.78	0.44	0.92	0.96	0.93	1.00	0.48	0.19	0.83
		MEDD	0.37	0.41	0.78	0.33	0.92	0.15	0.11	0.78	0.19	0.33	0.78
	COMPONENT B: Built Environment. Cultural Heritage & Infrastructure	WRNDI	0.44	0.30	0.93	0.19	0.75	0.78	0.78	0.70	0.44	0.37	0.83
		ESDI	0.85	0.85	0.19	0.59	0.17	0.07	0.07	0.15	0.26	0.22	0.22
		HFDI	0.93	0.70	0.30	1.00	0.08	0.41	0.41	0.52	0.56	0.56	0.28
		BCC	0.15	0.37	0.67	0.37	0.67	0.44	0.44	0.81	0.85	0.07	0.56
		CHSDI	0.07	0.07	0.19	0.15	0.08	0.44	0.44	0.00	0.70	0.04	0.17
	COMPONENT C: Economy & Society	RPDI	0.83	0.92	0.88	0.83	0.67	0.88	0.92	0.88	0.83	0.79	0.80
		EPR	0.79	0.46	0.50	1.00	0.33	0.63	0.67	0.75	0.79	0.50	0.60
		FRII	0.58	0.92	0.38	0.71	0.00	0.25	0.25	0.17	0.17	0.17	0.13
		EADI	0.42	0.58	0.88	0.25	1.00	0.67	0.71	0.96	0.63	1.00	1.00
		APER	0.83	0.88	0.50	0.71	0.11	0.21	0.21	0.17	0.17	0.29	0.13
		TPVI	0.42	0.88	0.92	0.63	0.22	0.54	0.63	0.54	0.54	0.33	0.27

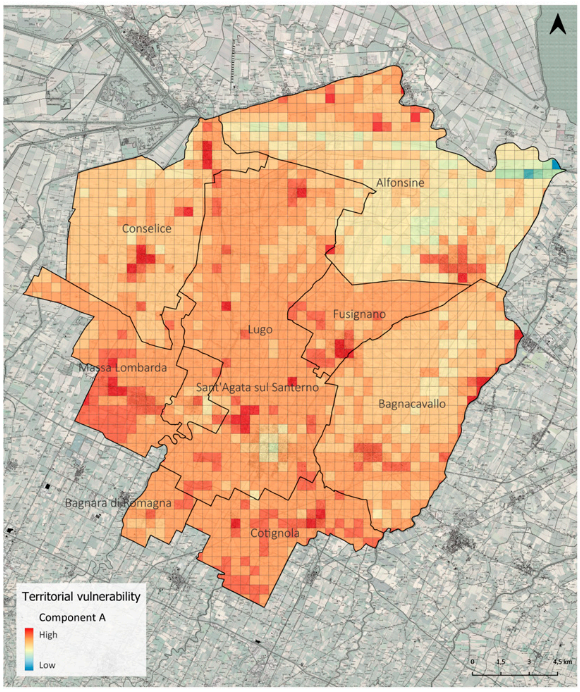
Once the indicators and vulnerability matrix are inserted into the plugin, it automatically processes the data and generates weighted vulnerability maps based on the values of the correlation matrix. The resulting vulnerability maps, presented in Figure 4, show the spatial distribution of vulnerabilities across the study area using the plugin. In particular, the first map represents the Total Vulnerability Index, while the following three maps represent the vulnerability regarding single components of the territorial system. This is achieved by assigning different weights in the last tab of the plugin (see Figure 2). The Total Vulnerability Index is generated by setting all values to 1. Component A Vulnerability, representing only environmental factors, is generated by setting the first two values to 1 and the remaining values to 0. The subsequent two maps are generated following the same principle. This feature of the plugin allows users to quickly identify vulnerable areas across the territory, either by considering all contributing factors or by isolating specific dimensions of the system.

As presented in the maps of Figure 4, a particularly illustrative case, but not limited to, can be the municipality of Lugo, the most populous area within the UBR. The Total Vulnerability Index map highlights consistently high vulnerability in the southern area of Lugo. This finding calls for closer analysis of the individual indicators and component-specific maps, which reveal important nuances. From an environmental perspective (Component A), Lugo's vulnerability is driven by a relatively low Permeable Land Surface Index (PLSI) and low Weighted Green Infrastructure Availability Index (WGIAI). In contrast, Component B—representing Built Environment, Cultural Heritage & Infrastructure—shows lower vulnerability, suggesting that Lugo benefits from relatively robust infrastructural conditions, including denser road networks (WRNDI) and better coverage of educational and healthcare facilities (ESDI and HFDI). However, the Building Construction Characteristics (BCC) indicate that the area is concentrated with old building stock. From a socio-economic perspective (Component C), the city exhibits lower capacities, characterised by a high Elderly Population Ratio (EPR), which amplifies vulnerability in the face of various hazards, including floods, heatwaves, and public health crises.

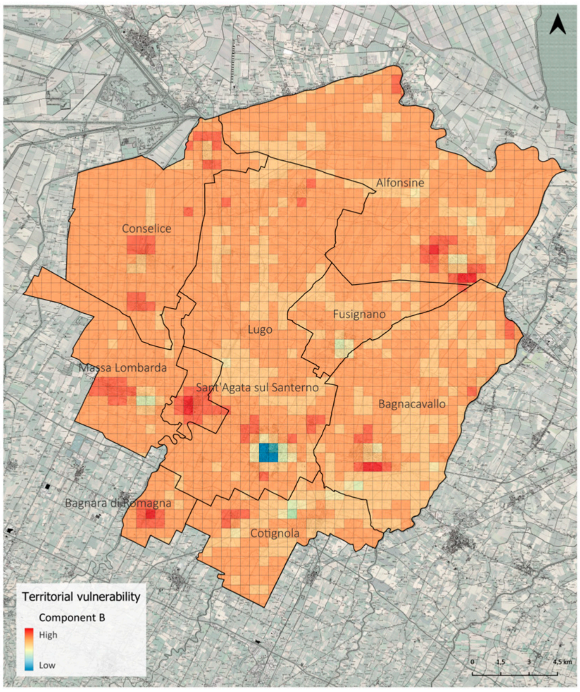
This example illustrates the importance of integrated and holistic vulnerability analysis in guiding targeted and effective resilience strategies. Even when one component in a city, such as infrastructure, performs well, the overall risk may remain high due to weaknesses in environmental or social dimensions.



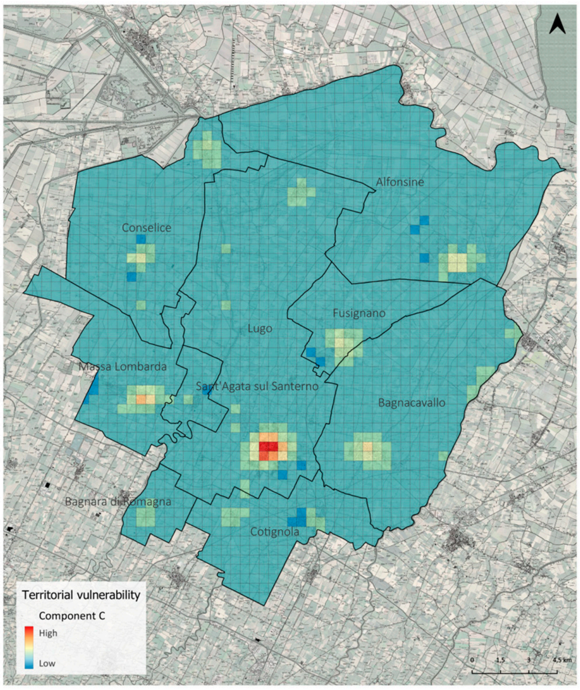
Total Vulnerability Index



Vulnerability Index regarding component **A**



Vulnerability Index regarding component **B**



Vulnerability Index regarding component **C**

Figure 4. The vulnerability maps generated using the R3C-GeoResilience Plugin.

Accordingly, the final phase of the participatory process involved a brainstorming session aimed at identifying potential adaptation and mitigation actions to enhance territorial resilience, based on the insights derived from the vulnerability maps. Among the proposed actions by the UBR local practitioners, participants emphasised the importance of nature-based solutions, such as implementing rain gardens for stormwater management and improved runoff control. They also recommended creating green islands and expanding urban green spaces, with a particular focus on developing a 'cool map' to highlight areas with naturally lower temperatures and to prioritise urban spaces for cooling interventions, ultimately contributing to the mitigation of heat-related risks. Furthermore, it was proposed to expand natural areas, enhance urban quality by reducing the impact of buildings, and promote new cycling paths to improve both mobility and sustainability. These proposals, as illustrated in Figure 5, represent a comprehensive, locally informed approach to addressing the territory's challenges, integrating environmental, social, and infrastructural considerations to foster more resilient urban spaces.

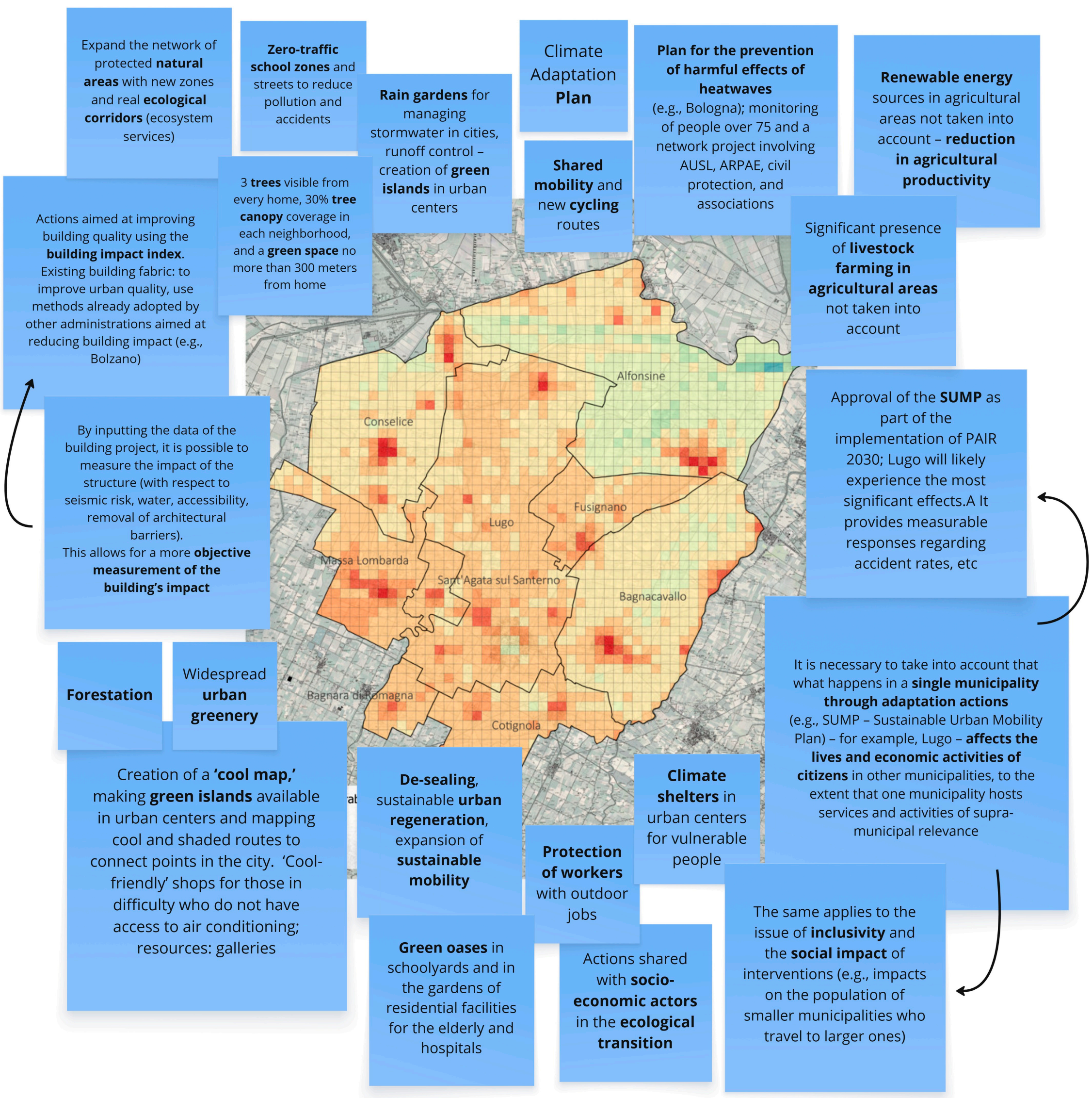


Figure 5. The results of the brainstorming session in the Miro Platform aimed at identifying potential adaptation and mitigation actions to enhance territorial resilience based on the generated vulnerability maps. Comments have been translated from Italian to English by the authors.

As presented above, the purpose of the R3C-GeoResilience tool is not limited to diagnosing territorial vulnerabilities. It also supports translating these findings into actionable resilience strategies. The logic of translation operates through different steps. First, the vulnerability maps provide a spatial diagnosis of the most fragile areas. Second, the component-based analysis (natural environmental, built environment, socio-economic) helps interpret which drivers are most critical in specific areas. Third, the participatory process enables prioritisation, ensuring that the most relevant local dynamics are taken into consideration. Subsequently, the results are translated into actionable pathways since the maps and matrices identify priority areas and the most influential drivers that can be addressed through targeted interventions such as nature-based solutions, infrastructure reinforcement, or social programmes. Finally, the actions can be incorporated into existing local governance and planning tools, including the General Urban Plan, Civil Protection plans, or resilience-oriented investment programmes. In this way, the tool creates a direct bridge from vulnerability mapping to resilience planning, supporting both immediate actions and longer-term strategies.

4. Conclusions

This study introduces a methodology and a developed GIS plugin designed as a spatially explicit and participatory tool for mapping localised territorial vulnerabilities. The analysis, conducted across nine municipalities in the Union of Bassa Romagna (UBR), shows the importance of analysing territorial vulnerabilities from a multi-risk and cross-sectoral perspective. This approach provides a more comprehensive basis for strategic planning and context-sensitive interventions in urban resilience policymaking. The empirical research highlights several benefits that bridge the gap between the conceptualisation and operationalisation of resilience, which are outlined below.

The participatory approach gave the tool clear policy relevance. By involving local officials in selecting and weighting indicators, the results were grounded in real territorial conditions and achieved institutional legitimacy. This cooperative process not only built local capacity for the practitioners of public administration but also increased the likelihood that adaptation and mitigation measures would be integrated into planning instruments such as the General Urban Plan and Civil Protection strategies.

In addition, the tool's open-source nature, flexible indicator system, and integration with GIS make it adaptable to a wide range of territorial settings. Vulnerability, by definition, is rooted in the specific territorial characteristics of each place and differs from broader concepts such as sustainability, for which universal Key Performance Indicators (KPIs) are more readily established. In contrast, vulnerability indicators—particularly those related to hazards—may be highly context-dependent, as specific hazards may be present in one territory and absent in another. Consequently, for each case study, tailored sets of indicators must be defined and calculated. What becomes crucial, therefore, is the availability of a methodological framework that enables the calculation of vulnerability indices according to a consistent logic across different territorial contexts. Such a framework enhances the feasibility of the assessment while ensuring comparability and coherence of results across diverse settings. The plugin's automation of technical steps further streamlines the mapping process, enhancing both feasibility and transferability. At the same time, successful replication requires three enabling conditions: (i) institutional commitment and inter-municipal cooperation to integrate results into planning instruments; (ii) basic GIS capacity supported by targeted training, as demonstrated in the *VALUE4UCBR* program; and (iii) access to reliable, disaggregated spatial data, which strengthens the robustness of outputs. Taken together, these conditions ensure that the tool can be effectively adapted and scaled to other contexts.

Turning to the limitations of this research, while the methodology provides a robust framework, its application is constrained by the availability and quality of spatial data. The inclusion of additional indicators is only possible where reliable datasets exist, and the lack of consistent time-series means that most indicators remain static, limiting the capacity to capture the temporal dynamics of resilience. Future research directions emerging from this study include tracking changes in territorial resilience over time through comparative mapping or the integration of dynamic spatial indicators that could capture the territorial dynamics. The research also suggests the need for ex-post evaluation, which can be achieved through the same set of indicators to assess the effectiveness of adaptation and mitigation measures, thereby supporting adaptive policymaking for long-term trends in land use, climate adaptation, and local development.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/urbansci9100400/s1, Supporting information is provided in Table S1, which includes the list of indicators used to calculate the vulnerability index, along with detailed information on how each indicator is calculated and the data sources used. In addition, Figures S1–S25 present the individual maps created for each of these indicators as follows: Table S1: List of indicators calculated to measure the vulnerability index; Figure S1: A1—Permeable Land Surface Index (PLSI); Figure S2: A2—Weighted Green Infrastructure Availability Index (WGIAI); Figure S3: A3—Cycling Infrastructure Density Index (CIDI); Figure S4: B1—Weighted Road Network Density Index (WRNDI); Figure S5: B2—Educational Services Density Index (ESDI); Figure S6: B3—Healthcare Facility Density Index (HFDI); Figure S7: B4—Building construction characteristics (BCC); Figure S8: B5—Cultural Heritage Sites Density Index (CHSDI); Figure S9: C1—Residential Population Density Index (RPDI); Figure S10: C2—Elderly Population Ratio (EPR); Figure S11: C3—Foreign Resident Incidence Index (FRII); Figure S12: C4—Economic Activity Density Index (EADI); Figure S13: C5—Active Population Employment Rate (APER); Figure S14: C6—Territorial Property Value Index (TPVI); Figure S15: T1—Structural Dependency Index (SDI); Figure S16: T2—Migration Dynamics Index (MDI); Figure S17: T3—Land Consumption Change Index (LCCI); Figure S18: T4—Aging Dynamics Index (ADI); Figure S19: T5—Chronic Air Pollution Exposure Index (CAPEI); Figure S20: E1—Historical Flood Frequency Index (HFFI); Figure S21: E2—Inundation Hazard Level Index (IHLI); Figure S22: E3—Bioclimatic Stress Index (BSI); Figure S23: E4—Seismic Liquefaction Risk Index (SLRI); Figure S24: E5—Industrial Accident Risk Index (IARI); Figure S25: E6—Short-Term Air Pollution Exposure Index (STAPEI).

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