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Co-Creating Multi-Hazard Resilience Indicators for Historic Environments: A Context-Specific Assessment Framework

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Abstract

Measuring the resilience of historic areas is challenging due to their heterogeneity in scale, heritage type, multi-hazard exposure, and socio-cultural context, creating the need for a flexible framework aligned with the latest Intergovernmental Panel on Climate Change (IPCC) approaches. This study introduces the SHELTER framework, which takes the historic area as its primary unit of analysis while enabling a cross-scalar assessment, from artefact/building scale to urban and transregional contexts. Developed through a co-creation strategy and an extensive literature review, the framework integrates indicators for multidimensional, cross-scale, and systemic resilience assessment and monitoring. The indicators span hazards such as heatwaves, earthquakes, floods, subsidence, and wildfires and capture exposure and vulnerability, the latter being understood as the sensitivity and coping, adaptive, and transformative capacities of communities. Refinement using the RACER methodology yielded a concise yet comprehensive shortlist of indicators, providing both general overviews and specific insights tailored to historic environments. The framework's efficacy was tested across five case studies, demonstrating adaptability and suitability in diverse historic areas. Overall, SHELTER moves beyond a traditional focus on physical vulnerability and risk management, offering a replicable, holistic set of resilience indicators that supports consistent assessment and monitoring while respecting the singularities of historic settings.

Keywords: historic environments; indicator-based assessment; multi-hazard resilience assessment; urban resilience disaster risk management; decision making urban conservation

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1. Introduction

Historic areas (HAs), in UNESCO's sense, are recognized groupings of buildings, structures, and open spaces forming urban or rural settlements of acknowledged archaeological, architectural, historic, aesthetic, or socio-cultural value [1]. In addition to human-induced threats such as over-tourism, urbanization, and pollution, HAs are facing a wide range of natural hazards and extreme events which are increasing in frequency, duration, and intensity due to the climate emergency [2,3], a trend that is expected to continue in the future [4]. HAs, due to factors like the age of their fabric or the density and morphology of the urban structure, are particularly vulnerable to these threats compared to modern environments [2,5]. Because the loss of cultural and historical values is often irreversible, inadequate preparedness for disaster risk management (DRM), particularly for climate-related hazards, remains a major concern for heritage managers, as UNESCO has repeatedly underscored [6]. This perspective accords with UNESCO's 2011 Recommendation on the Historic Urban Landscape, which promotes a holistic understanding of urban heritage and calls for inclusive, participatory governance and risk-informed management, including the assessment of vulnerability to socio-economic pressures and the impacts of climate change [7].

Operationalized with stakeholders, resilience is an effective lens for climate-risk and uncertainty analysis, fostering adaptability, learning, and flexibility [8]. In the UNDRR Sendai Terminology, "resilience" is defined as the ability of a system, community, or society exposed to hazards to resist, absorb, accommodate, adapt to, transform, and recover from the effects of a hazard in a timely and efficient manner; risk is framed and monitored under the Sendai targets and indicators. Specifically, the SHELTER project defined the resilience of HAs as "the ability of a historic urban or territorial system-and all its social, cultural, economic, environmental dimensions across temporal and spatial scales to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and use it for a systemic transformation to still retain essentially the same function, structure and feedbacks, and therefore the capacity to adapt to maintain the same identity" [9]. Beyond the mere conservation of values, resilience in HAs should mobilize cultural and natural heritage as active resources to confront emerging threats [10]. For example, traditional building techniques have shown earthquake resilience, providing valuable precedents for contemporary design and construction [11]. To ensure that risk is addressed holistically, and that heritage authenticity is preserved, these heritage-based strategies must be integrated with DRM and climate change adaptation (CCA) efforts [3,5].

One of the priorities outlined in the Sendai Framework is understanding risk, i.e., the identification, assessment, and monitoring of risks [12]. The use of indicator-based resilience assessments can contribute to enhancing awareness, decision-making processes, and monitoring strategies [13]. However, despite being a global priority, the measurement of resilience is still an ongoing endeavor that requires the identification of observable and measurable variables that encompass the conceptual and abstract term of resilience [8,14,15]. Measuring resilience in HAs is particularly complex due to their heterogeneous nature, as these areas are the result of century-old processes of adaptation to their surrounding environments and territories [16]. They vary in size, types of heritage, governance models, and community values and priorities. Additionally, they face different hazards, vulnerability conditions, and data availability. Consequently, resilience assessment procedures for HAs must be adaptable, replicable, and applicable across scales, hazard types, and multi-hazard settings, while explicitly accounting for diverse socio-cultural contexts, stakeholder interests, local circumstances, and community [17,18], and they must include cultural and community values as well as estimations of authenticity and integrity [5].

In short, the methodologies and processes for resilience assessment in HAs should be tailored to the heritage-specific context [3], but despite advances in resilience theory and assessment methods, a clear scientific gap persists regarding their applicability to historic areas. Existing indicator-based frameworks tend to be either (i) hazard-specific, lacking integration into multi-hazard contexts [2,19]; (ii) focused on contemporary urban systems, with limited consideration of heritage authenticity, integrity, and socio-cultural values [20] (although there are some notable exceptions [21–23]); or (iii) constrained to a single spatial scale, without addressing cross-scalar interactions between buildings, urban morphology, and broader territorial systems. Recent systematic reviews show that resilience assessment remains overwhelmingly single-scale, with only a marginal fraction of studies adopting multi-scalar approaches or examining interactions between buildings, urban morphology, and territorial systems [24,25].

Furthermore, most existing approaches do not operationalize IPCC AR6 risk framing in a manner that is usable for heritage managers or compatible with heritage-specific governance models [26]. As highlighted in recent academic literature, resilience assessment for heritage remains fragmented, insufficiently multi-scalar, and rarely aligned with both DRM and CCA needs [27].

This paper directly addresses these gaps by documenting the co-design, refinement, and validation process that produced a usable framework comprehensive enough to address all of the dimensions of resilience in HAs and flexible enough to allow tailoring of assessment and monitoring to specific contexts, considering factors such as the hazards faced, scale, and data availability. Its novelty lies in operationalizing IPCC AR6 risk framing, linking hazard, exposure, and vulnerability (including risks from responses), into a monitoring-ready, indicator-based architecture aligned with UNESCO's Historic Urban Landscape principles. The process is explicitly designed to distil conceptual guidance and measurable constructs from existing frameworks, and to translate them into practical, context-adaptable indicators. The framework combines hazard-specific metrics with hazard-agnostic capacities (coping, adaptive, and transformative), refines indicators using the RACER criteria to ensure relevance, credibility, and usability with public data, and demonstrates replicability across five diverse cases [28]. Rather than merely describing a framework, this article analyses the process through which it was developed, refined, and validated with stakeholders across heterogeneous historic areas.

2. Materials and Methods

The SHELTER framework is designed to facilitate the co-creation of resilience assessment and monitoring, specifically targeting the strategic phases of DRM, such as prevention and recovery [26]. It aims to integrate multi-scalar physical vulnerability and risk management concepts, following the latest approaches of the Intergovernmental Panel on Climate Change (IPCC) [17]. Moreover, it incorporates a broader, multidimensional resilience approach tailored to the unique characteristics of HA. To achieve this, the framework distinguishes between general resilience and specified resilience. General resilience, or non-hazard-dependent resilience, encompasses the ability to withstand various impacts and disturbances, including unforeseen ones. Specified resilience, or hazard-dependent resilience, addresses challenges specific to hazards affecting distinct components of socio-ecological systems [29]. The difference between hazard-dependent and non-dependent elements can be therefore described as related to their predictability.

The framework is designed to accommodate the heterogeneity of historic areas, as defined by UNESCO, and the selection of the five Open Labs—Ravenna (Italy), Seferihisar (Turkey), Dordrecht (Netherlands), the Natural Park of Baixa Limia–Serra do Xurés (Spain), and the Sava River Basin (South-Eastern Europe)—following a structured methodological selection process. The sites were selected to systematically span (i) heritage diversity, from archaeological complexes to urban ensembles and transboundary cultural landscapes; (ii) varied hazard profiles, including earthquakes, floods, storms, subsidence, wildfires, and heatwaves; (iii) multiple spatial scales and typologies, ranging from single buildings and districts to cities, regions, and cross-regional basins; and (iv) contrasting planning systems, governance arrangements, and participatory capacities, including differences in disaster-risk-management experience, co-creation maturity, and information infrastructures. This structured heterogeneity ensures that the framework is tested under maximally contrasting socio-ecological and institutional conditions, enabling methodological validation, generalizability, and cross-case replicability. This heterogeneity is illustrated in the following table (see Table 1).

Table 1. Selection and characterization of case studies (1 = primary, 2 = secondary).

		Santa Croce	Seferihisar	Dordrecht	Baixa Limia	Sava River
Affected population		5000	31,400	118,000	1,614,535	9,000,000
Geographical zone (EU)		South	South-East	North	South-West	Central-East
Demo scales	Building	1	2	2	2	2
	District	2	1	2	2	2
	City		2	1	2	2
	Region				1	2
	Cross-regional				2	1
Hazards	Earthquakes	2	1			
	Storms		2	2		
	Floods	1	2	1		1
	Heat waves		2			
	Wildfire		2		1	
	Subsidence	2				
Governance and planning	Level of experience in DRM instruments	High experience in Emergency Operative Plans	Medium. Heatwave warning system and earthquake recovery	High. Protection plans local and national protocols for evacuation	Medium–High. Civil Protection Plan for forest fires	High experience in transboundary protocols
	Experience in co-creation	Medium	Medium	High	Medium	High
Heritage Values	Type of heritage	Immaterial, archaeological and urban	Immaterial, urban, earthen architecture	Immaterial, urban and industrial	Immaterial, natural and cultural	Immaterial, natural and cultural
	Level of protection	Very High	Medium	High	Medium	Medium
Existing data/tools	Level of information	Medium	Medium	High	High–Medium	High–Medium
	Type	GIS, Cultural Heritage Catalogue and documentation, 3D model of the site, subsidence monitoring (level, GNSS, interferometric)	GIS, Cultural Heritage Catalogue, 3D models, data on protected area boundaries, mobile App. on Google Play	GIS, Cultural Heritage Catalogue, flood risk database and monitoring, climate change impact analysis, 3D models	GIS geoportal and databases, Cultural and Natural Heritage Catalogue and geoportal	GIS geoportal, flood risk maps and analysis, material studies, Digital Elevation Model based on LIDAR, hydraulic model

The Open Lab (OL) concept facilitates a robust stakeholder-centered approach by functioning concurrently as a multi-actor environment for knowledge generation, evaluation and demonstration, and contextual adaptation. The OLs encompass the entire resilience value chain, including local authorities, heritage managers, practitioners, SMEs, citizens, and vulnerable groups, and engage these actors in workshops held every six months for creation and co-validation processes aimed at collaboratively shaping and refining place-based resilience strategies.

The development of the assessment and monitoring framework followed a logical sequence, outlined as follows (see Figure 1):

- Framework design: Integrated existing models to define the SHELTER framework's architecture and its elements and dimensions for assessing and monitoring hazard impacts, which then guided the indicator measurement objectives.
- Indicator selection: Conducted a structured literature review; screened candidates with RACER (Relevance, Acceptability, Clarity, Easiness, Robustness); ran a gap analysis to cover unmet objectives. The outcome from this step were the SHELTER resilience indicators.
- Contextualization: Co-created tailored frameworks within each Open Lab (OL) to align with local contexts, needs, and capacities.

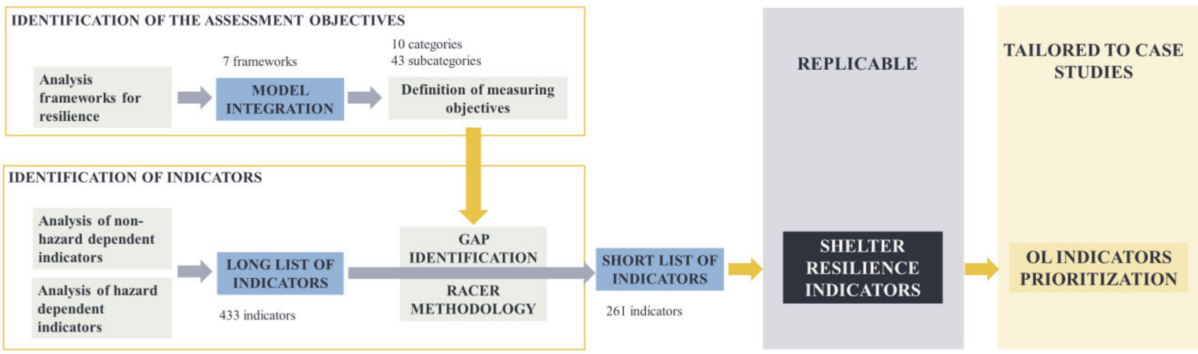

Figure 1. SHELTER methodological approach, and frameworks and indicator filtering in each step.

2.1. *Building the SHELTER Framework: Identification of the Objectives for the Assessment*

As a first step, various frameworks aiming to operationalize resilience were reviewed to identify and compare how the elements of risk and resilience were considered. Table 2 describes the identified frameworks.

Table 2. Resilience frameworks.

Model	Description	Source
SPRC	The Source–Pathway–Receptor–Consequence (SPRC) is a conceptual model linking hazards to consequences through pathways and receptors, emphasizing that outcomes depend on exposure and vulnerability rather than hazard alone.	[30]
SPRC EXT.	An extended version of SPRC with a broader notion of resilience that includes risk-reducing measures and the recovery phase.	[31]
IPCC/ SREX	Developed by IPCC Working Groups I and II, the Special Report on Managing the Risks of Extreme Events and Disasters (SREX) addresses links between climate change, extreme events, and disaster risk management, framing decision-making under uncertainty for adaptation strategies.	[32]
DPSIR	The Driver–Pressure–State–Impact–Response (DPSIR) framework developed by the Organization of Economic Cooperation and Development and the European Environment Agency conceptualizes causal chains from socio-economic drivers through environmental pressures to system states, impacts, and policy responses, supporting integrated environmental assessment.	[33,34]
DRIB	Risk index integrating exposure, susceptibility, coping capacity, and adaptive capacity. Based on the World Risk Index, it provides a holistic view of vulnerability and resilience.	[35]
PAR	The Pressure and Release (PAR) model explains disaster risk as the interaction between natural hazards and social vulnerability, highlighting root causes, dynamic pressures, and unsafe conditions that amplify risk.	[36]
EEA	Framework supporting urban adaptation and transformation toward climate-resilient, sustainable, and attractive cities, emphasizing systemic approaches to resilience planning.	[37]

Because the reviewed frameworks differ in conceptual scope and operational maturity, we applied a harmonization procedure to extract only comparable conceptual components, hazard, exposure, and vulnerability (as an umbrella concept encompassing sensitivity and capacities), from all frameworks, and to translate operationally mature elements directly into measurement objectives.

To support consistency in terminology and ensure alignment across frameworks, the key concepts related to capacities are defined as follows:

- Adaptive capacity: The ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences [38].
- Coping capacity: The ability of a system—human or natural—to respond to and recover from disruptions that have the potential to change its structure or function [32].
- Transformative capacity: The ability of individuals or organizations to intentionally and consciously transform themselves and their society [39].

As the second step, the IPCC AR6 risk framework was examined to improve assessment by addressing interactions among determinants and multiple, overlapping risks. AR6 conceptualizes risk as a dynamic function of hazard, exposure, and vulnerability, the latter comprising sensitivity and coping/adaptive (and potentially transformative) capacities. It additionally recognizes response-driven risks (trade-offs, maladaptation), underscoring analysis of both component drivers and their cross-risk interactions [40]. Table 3 presents the outcome of this model comparison and integration.

Table 3. Comparative analysis of resilience models and their integration within the SHELTER framework. Grey cells indicate elements not explicitly addressed by the respective models. SHELTER provides a comprehensive integration of all key components—hazard, exposure, vulnerability, disaster risk management (DRM), climate change adaptation (CCA), cultural heritage management (CHM), consequences, and recovery—offering a systemic approach tailored to historic environments.

Source	**Elements of Resilience**										
	Risk						**Measures**			**Consequences**	**Recovery**
SPRC	Source	Pathway	Receptor							Consequences	
SPRC EXT.	Source	Pathway	Receptor				Measures			Consequences	Recovery
IPCC/SREX	Hazard	Exposure	Vulnerability				DRM	CCA			
			Sensitivity		Adaptative capacity						
DPSIR	Source									Impacts	Response
DRIB		Exposure	Vulnerability								
			Susceptibility	Coping capacity		Adaptative capacity					
PAR	Hazard	Vulnerability									
		Root causes	Dynamic pressures		Unsafe conditions						
EEA				Coping	Incremental adaptation	Transformational adaptation					
SHELTER	Hazard/source	Exposure/pathway	Vulnerability				DRM	CCA	CHM	Casualties	Recovery rate
			Sensitivity	Coping capacity	Adaptive capacity	Transformative capacity					

As a result, in this study resilience is conceptualized as a dynamic function of risk, encompassing the capacity to reduce risk, absorb impacts, recover functionality, and integrate learning for future preparedness. Risk itself emerges from the interaction of hazard, exposure, and vulnerability, forming the core determinants of potential disruption. Vulnerability is not a static condition but a dynamic, multifaceted condition encompassing sensitivity and the capacities to cope, adapt, and transform in response to stressors. These capacities operate across temporal and spatial scales, influencing both immediate responses and long-term system evolution. The SHELTER framework advances this conceptualization by integrating all key resilience elements, hazard, exposure, vulnerability, DRM, CCA, CHM, consequences, and recovery, into a single operational model. This systemic approach is unique in embedding CHM within resilience assessment, addressing a critical gap in existing frameworks. In HAs, transformative capacity acquires a distinctive dimension: disruptions in use, such as those triggered by extreme events, can catalyze beneficial reconfigurations of socio-cultural and physical systems, provided that heritage values are safeguarded.

The comparison of the models enabled the identification of essential resilience elements to measure, leading to the delineation of measuring objectives (see Table 4). Appendix C details how these objectives emerge from the model integration. This is an important step to define indicators that facilitate the measurement of these dimensions. Objectives that are hazard-dependent are highlighted in yellow, while the ones that are non-hazard-dependent are highlighted in orange.

Table 4. Role of the indicators (measuring objectives).

Prevention		Recovery
Measuring Risk		Measuring Consequences
Measuring hazards	Frequency	
	Magnitude	
	Duration	
	Intensity	
Measuring exposure	Individuals	Casualties
	Community	
	Processes	Loss: Indirect and economic
	Activities	
	Object/buildings/infrastructure	Damage in buildings/infrastructure/objects/ecosystems
	Ecosystems	
Measuring sensitivity	Social/demography characteristics	
	Economic characteristics	
	Building/infrastructure characteristics	
	Environmental sensitivity	
Measuring coping capacity	Awareness/information	
	Networks/solidarity/community preparedness	
	Insurance/funds	
	DRM	
	Social memory	
	Shelter capacity	
	Protection of natural resources	
Measuring adaptative capacity	Human capital/education	Recovery rate/reparability/informing Sendai monitoring
	Social capital/learning	
	Economic capital	
	Institutional capital/governance	
	Cultural capital/identity	
	Built capital/infrastructure	
	Natural capital	

Table 4. *Cont.*

	Prevention	Recovery
Measuring transformative capacity/inherent resilience	Social memory/living with uncertainty	Recovery rate/reparability/informing Sendai monitoring
	Self-organization; reflective and shared learning	
	Resourcefulness/efficiency	
	Collaboration/inclusive/diversity/intersectoriality	
	Innovation	
	Robustness/strength/appropriately connected	
	Coupled with local natural capital	

2.2. Identification of Indicators

Different resilience concepts can be systematically mapped and integrated using a three-dimensional framework consisting of four quadrants, delineated by two axes representing hazard predictability and spatial scale [41]. The definition of this framework was drafted in an early stage of the project [42] where mandatory requirements were agreed: (i) inclusion of both generalized (hazard-independent) and specified (hazard-dependent) resilience, (ii) cross-scalar applicability from artefact/building up to urban or transregional historic areas (HA), (iii) multidimensionality covering physical, social, economic, institutional, and cultural domains, and (iv) the treatment of resilience, vulnerability, and adaptive capacity as nested concepts. This structure enables the classification of indicators into specified resilience (hazard-dependent) and generalized resilience (non-hazard-dependent) based on their scale (Figure 2). The Y-axis reflects the degree of hazard predictability, distinguishing generalized resilience (upper half) from specified resilience (lower half), while the X-axis represents the geographical scale of the HA. A third dimension, the Z-axis, introduces a temporal perspective, accounting for future impacts and supporting resilience and risk monitoring over time. Together, these axes provide a comprehensive basis for organizing indicators and understanding resilience dynamics across spatial, temporal, and hazard-related dimensions.

The literature review provided an extensive set of indicators addressing both hazard-specific resilience, covering heatwaves, earthquakes, floods, subsidence, and wildfires, and generalized resilience, including measures of coping, adaptive, and transformative capacities within communities. Scopus was queried with a set of Boolean strings covering the five HA-resilience dimensions (physical, social, economic, institutional, and cultural) and the eight hazard categories. The first screening of 744 records was performed on abstracts and classified on a four-point relevance scale (0 = not relevant; 1 = potentially interesting; 2 = clearly addresses at least one assessment quadrant or resilience dimension; 3 = focuses on historic areas and/or provides indicator systems). A second, more detailed screening extracted metadata on (i) historic-area focus, (ii) resilience dimension, (iii) hazard type, (iv) assessment quadrant (QA–QD), (v) presence of indicator sets, and (vi) review status.

The outcome of the two-stage screening identified those papers that used indicators in their methods, resulting in the detection of 433 indicators, which were then mapped against predefined measurement objectives to detect gaps where objectives lacked corresponding indicators. To ensure comprehensive coverage across all hazards and resilience dimensions, a targeted review was conducted to fill these gaps, drawing particularly on insights from the EMBRACE project, which proved instrumental in refining the indicator set [43]. The final list of indicators (see Appendix A) shows the measuring objective that each indicator is addressing.

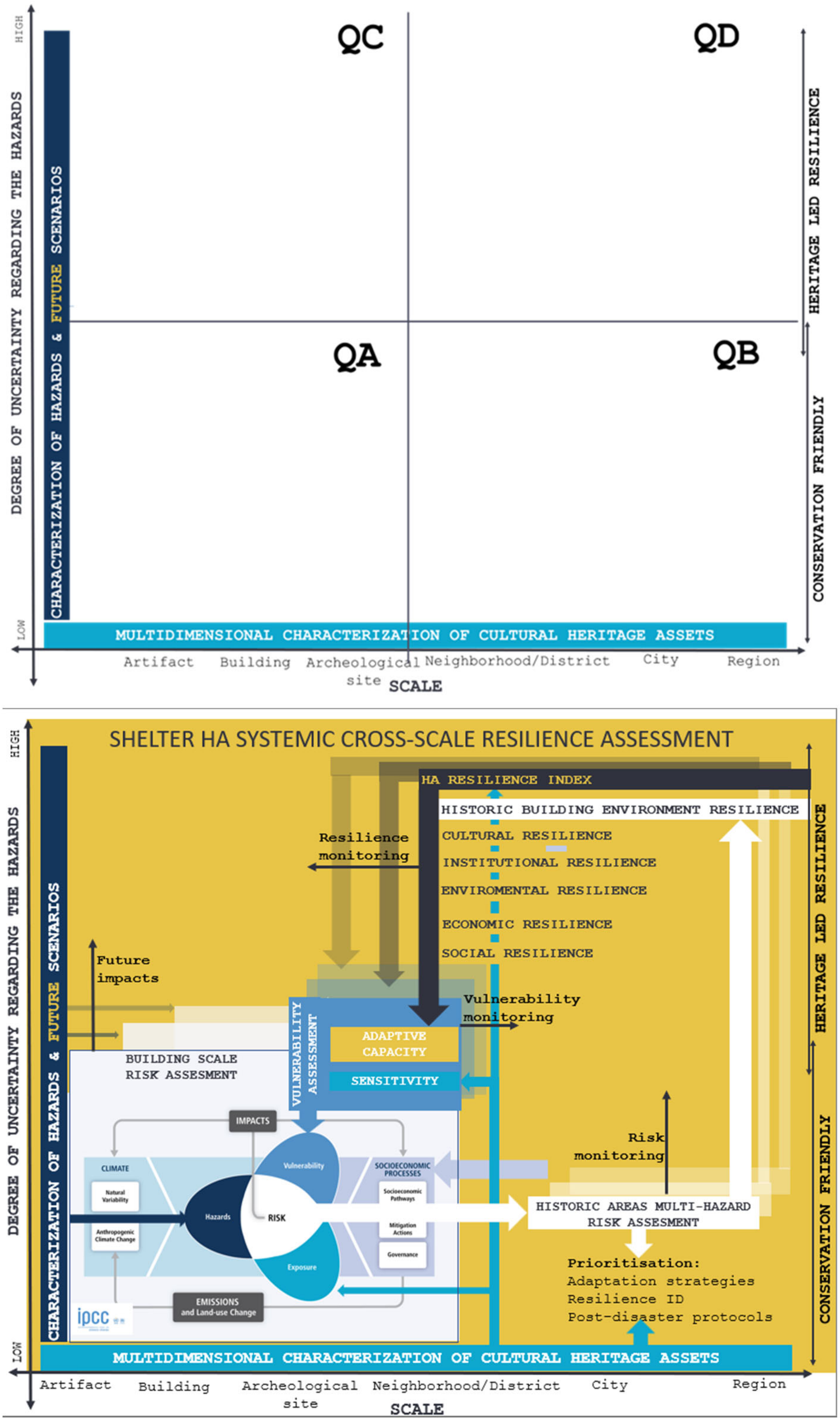

Figure 2. SHELTER resilience assessment strategy.

To evaluate the suitability of the selected indicators, the RACER framework (relevant, accepted, credible, easy, and robust) was applied [28]. Originally developed to assess the effectiveness of scientific instruments in supporting policy decisions and previously adapted for cultural heritage contexts [44], this methodology enabled a systematic refinement of the initial indicator set.

For each of the five RACER criteria, a set of two sub-criteria was defined (Table 5).

Table 5. RACER criteria and sub-criteria.

RACER Criteria	Sub-Criteria (Assessment Question)
Relevant	1. Is the indicator meaningful for resilience assessment? 2. Is the indicator comparable across sites or time?
Accepted	1. Has the indicator been previously used in heritage or resilience studies? 2. Is the indicator a standard (e.g., recognized by international guidelines)?
Credible	1. Is the indicator unambiguous (single, clear definition)? 2. Does it have a transparent methodology for calculation?
Easy	1. Are the data required for the indicator available? 2. Is the indicator easy to calculate (low computational or logistic cost)?
Robust	1. Does the calculation rely on real data rather than estimations? 2. Is the indicator applicable to similar cases? 3. Is the indicator applicable across all European and SHELTER countries (including Turkey)?

Each sub-criterion was scored independently by a member of the research team according to his/her expertise, on a four-point scale (0 = does not meet the criterion; 1 = somewhat meets; 2 = almost meets; 3 = totally meets). The score for a given criterion was calculated as the arithmetic mean of its two sub-criteria (e.g., relevance = (meaningful + comparable) ÷ 2).

The overall RACER score for an indicator was then obtained with a weighted sum that gives extra weight to relevance:

$$Final\ score = \frac{3 \times \text{Relevance} + \text{Acceptance} + \text{Credibility} + \text{Easiness} + \text{Robustness}}{7}$$

Indicators attaining a final score > 2.0 were retained. Through this process, the list was reduced to a shortlist of 261 indicators, forming the replicable SHELTER resilience indicators and monitoring indicators designed to assess resilience and support long-term monitoring strategies in HAs.

2.3. Co-Creation of the Indicators with Case Studies

The contextualization and prioritization of the indicators based on the SHELTER resilience indicators constituted the subsequent step to formulate tailored strategies for the five complementary Open Labs (OLs). To determine the operational applicability of the methodology and link data availability to specific locations, a refinement and relevance-testing process was conducted through workshops, aiming at building a co-designed tailored resilience assessment for each OL. This process considered the type of heritage, the hazards faced, and the scale of each case. Given the wide scope of the resilience assessment, broad stakeholder participation with diverse expertise was deemed appropriate through workshop exercises.

To ensure methodological rigor, the process followed a multi-step workflow where stakeholder input did not stand alone but complemented the previous technical screening. Specifically, as detailed before, the initial pool of indicators, gathered from the literature review, was first refined by 10 independent experts through the RACER criteria to ensure suitability and operability, resulting in the 261-indicator shortlist to be discussed with the OL according to their diverse contexts. In parallel, academic partners were invited to review and comment on the completeness and coherence of the framework. Indeed, the

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objective of the exercise was to reduce the list of indicators into a manageable number of entries for each OL while ensuring coverage of key issues relevant for each of them.

As a first step, a tailored list of indicators was prepared for each workshop exercise, filtering hazard-dependent indicators according to the specific hazards faced by each OL. Subsequently, relevance-testing in the OLs followed a structured co-creation methodology where stakeholders were asked to rate the relevance of each indicator in measuring resilience against specific hazards in their HAs, as well as their feasibility in terms of data availability and timely collection. The direct engagement of technical stakeholders allowed for a further critical gap analysis based on the needs of each site, identifying specific missing indicators essential for capturing the unique environmental and cultural drivers of these contexts. This approach ensured that the final selection was evidence-informed and grounded in locally verifiable conditions rather than subjective preference.

The resulting variability in the final list (21–59 indicators according to the different OLs) reflects a context-sensitive tailoring necessary to maintain methodological consistency across different hazards, contexts, and governance structures. As a last step, each OL sought consensus on the final list and rating of indicators among the stakeholders involved.

2.4. Hazard-Dependent Indicators: Hazard, Exposure, and Vulnerability

As outlined in Section 2.1, the hazard-dependent risk assessment followed the IPCC approach, where risk is understood as a function of hazard, exposure, and vulnerability. Each considered hazard was characterized by the exposure and vulnerability of cultural and natural heritage to their respective impacts. A detailed description of this characterization can be found in [45]. Certain indicators were customized to accommodate the specific characteristics of the hazard, recognizing that their impacts vary and result in diverse damage, depending on the cultural elements under consideration. This comprehensive assessment ensured a tailored approach to addressing the specific risks posed by each hazard to the heritage sites and natural environments considered in this research. Although the indicators presented in this section span environmental, social, and infrastructural domains, they are not aggregated into composite or cross-domain indices. Instead, they are analytically structured according to the IPCC AR6 risk framework, where hazard, exposure, and vulnerability are treated as distinct but interacting components. Aggregation is deliberately avoided at this stage to preserve causal transparency and to support context-specific interpretation in historic areas; integration across domains occurs later at the decision-support level rather than through mathematical aggregation. The table below summarizes key factors for hazard characterization, exposure, and vulnerability across the considered hazards (see Table 6).

Table 6. Indicators for hazard characterization, exposure, and vulnerability for earthquakes, wildfires, heatwaves, storms, floods, and subsidence, including supporting literature.

Hazard	Hazard Characterization	Exposure	Vulnerability	References
Earthquakes	- Intensity (magnitude, modified Mercalli scale) - Peak ground acceleration (PGA) - Seismic zones (PGA-based maps)	- Soil type (amplifies seismic effects) - Geomorphology (topographic coefficient) - Critical facilities (industrial, environmental risks)	- Construction period/technology - Structural alignment/maintenance - Material degradation - Seismic engineering standards	[46–49]

Table 6. *Cont.*

Hazard	Hazard Characterization	Exposure	Vulnerability	References
Wildfire	- Climate variables (temperature, heatwaves, precipitation) - Fuel accumulation - Topography (slope, elevation, land configuration)	- Climate change (warmer conditions, longer fire seasons) - Proximity to residential areas (Portugal, Spain, France, Greece, Italy)	- Biodiversity/landscape loss - Proximity to human activities (roads, vegetation type) - Vegetation density (NDVI, LST)	[50–54]
Heat Waves	- Temperature/relative humidity (RH) thresholds - Thermal shocks (daily RH cycles, sun hours)	- Urban form (sky view factor, urban canyons) - UHI effect (albedo, thermal diffusivity) - Ozone (O_3) levels and acoustic pollution	- Traditional materials (weathering sensitivity) - Building typology (construction year, insulation, conservation status)	[17,55–74]
Storms	- Wind speed/gust strength - Air pressure - Storm duration/frequency - Lifted/cape indices	- Asset location (wind pressure, wind channels) - Infrastructure pre-damage - Forest windthrow indicators	- Storm-resistant building proportion - Mortality/hospitalization rates - Media coverage (public awareness)	[32,38,75–84]
Floods	- Precipitation patterns (seasonal variations, intensity) - River basin morphology - Flood severity/magnitude	- Flood-prone areas (return periods, climate scenarios) - Urban infrastructure (buildings, utilities)	- Cultural heritage sensitivity (materials, elevation, conservation status) - Drainage system condition (green roofs)	[37,85–88]
Subsidence	- Subsidence rate (mm/year, isokinetic maps) - Groundwater extraction, mining, permafrost thaw	- Homogeneous vs. differential settlement - Proximity to ground-water/surface water levels	- Deflection ratio (differential settlement) - Flood risk in low-lying areas (elevation < sea level)	[89]

2.5. Hazard Non-Dependent Indicators

The hazard non-dependent indicators aim to complement the hazard-dependent risk assessment and quantify generalized resilience, helping us to understand and improve community resilience by measuring cultural and socio-demographic contexts, as well as the coping, adaptive, and transformative capacities of socio-ecological systems.

A literature analysis of hazard-non-dependent indicators was undertaken using Edgemon et al.'s Community Resilience Indicator Analysis: County-Level Analysis of Commonly Used Indicators from Peer-Reviewed Research as the starting point [49]. In that work, six meta-analyses of peer-reviewed community-resilience assessment methodologies, Cutter (2015) [90], Koliou et al. (2018) [91], Lavelle et al. (2015) [92], Sharifi et al. (2016) [20], and Winderl (2014) [15], were examined, from which 27 methodologies were identified. To determine useful indicators, these 27 methodologies were narrowed to 11 (see Table 7) according to four screening criteria: (i) a focus on basic-needs provision (food security, humanitarian support, water scarcity, poverty, health, drought); (ii) applicability at the community level; (iii) inclusion of quantitative indicators; (iv) use of publicly accessible data sources. This subset was then employed to inform the operationalization of hazard-independent categories and the associated measurement objectives.

Table 7. Selected resilience indicators frameworks and selected indicators.

Code	Name	Source	Selected Indicators
BRIC	Baseline Resilience Indicators for Communities (BRIC)	[93]	25
CDRI	Community Disaster Resilience Index	[94]	9
CDRI-I	Community Disaster Resilience Index (Italy)	[95]	8
CR-E	Community Resilience in Disaster-Prone Districts	[96]	3
CRI2	Community Resilience Index	[97]	1
DROP	Disaster Resilience of Place	[98]	6
ODI	Overseas Development Inst.	[99]	11
PVI	Prevalent Vulnerability Index	[100]	12
ResilUS	Resilience Institute	[101]	6
SVI	Social Vulnerability Index	[102]	4
TNC	The Nature Conservancy Coastal Resilience Mapping Tool	[103]	5

Within resilience-indicator frameworks, the indicators employed here map to all measurement objectives of the SHELTER framework while remaining hazard-agnostic. They quantify generalized community attributes (socio-demographics, education, transport and access, communications, infrastructure and services, employment and livelihoods), as well as outcome metrics such as mortality, losses, and recovery. Where multiple, comparable indicators were identified across source frameworks, the variant best suited to HAs was retained.

3. Results

3.1. The Final List of Indicators

The final shortlist comprised 261 indicators, each systematically characterized to ensure clarity and applicability. For every indicator, we documented: its identification number (maintained throughout the process), the disaster risk management (DRM) phase to which it applies, the risk component and its specific aspect, a description of the indicator scope, denomination, measurement variable and unit, the resilience dimension assessed, associated hazard(s), spatial scale, temporal frequency, and validation results from case studies (evaluating relevance and feasibility). The complete list of indicators and their characterization is provided in Appendix A. To illustrate the distribution of indicators across different measuring objectives, Figure 3 presents a tree-map visualization. This representation highlights the predominance of indicators related to sensitivity, hazard sources, and coping capacity, while also showing the relative weight of objectives such as adaptive capacity, exposure, and transformative resilience. The full list of indicators and their characterization can be found in Appendix A.

To facilitate implementation in the case studies, a factsheet for each indicator was developed. These factsheets served as a standardized operational protocol providing stakeholders with structured and essential technical details, including the specific data requirements, the level of calculation complexity, and the necessary tools or software. Furthermore, the factsheets guided the calculation process through detailed formulas or descriptions, ensuring that the HAs' singularity (indicators specifically addressing cultural and natural heritage) was correctly captured across diverse scales. The structure of this factsheet, which includes the descriptive and technical fields to ensure methodological consistency, can be seen in Appendix B.

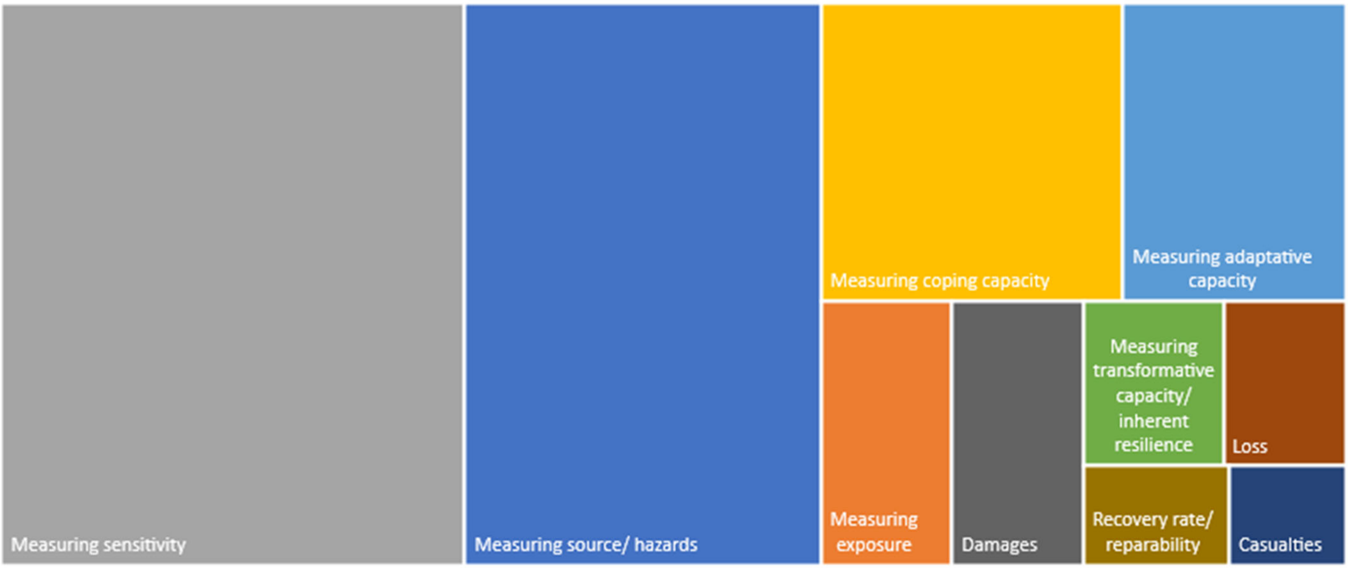

Figure 3. Distribution of the number of indicators for measuring objectives. Each color corresponds to a distinct measuring objective, as labeled directly within the figure.

3.2. Tailored Monitoring Strategy for Open Labs

Using the shortlist, the OLs co-created their resilience assessment and monitoring strategy with the indicators that were considered most relevant for their context. The tailored strategy has been validated during workshops and agreed upon among stakeholders. The following figure (Figure 4) shows the number of indicators which were considered essential for the resilience assessment and monitoring that are available in each OL.

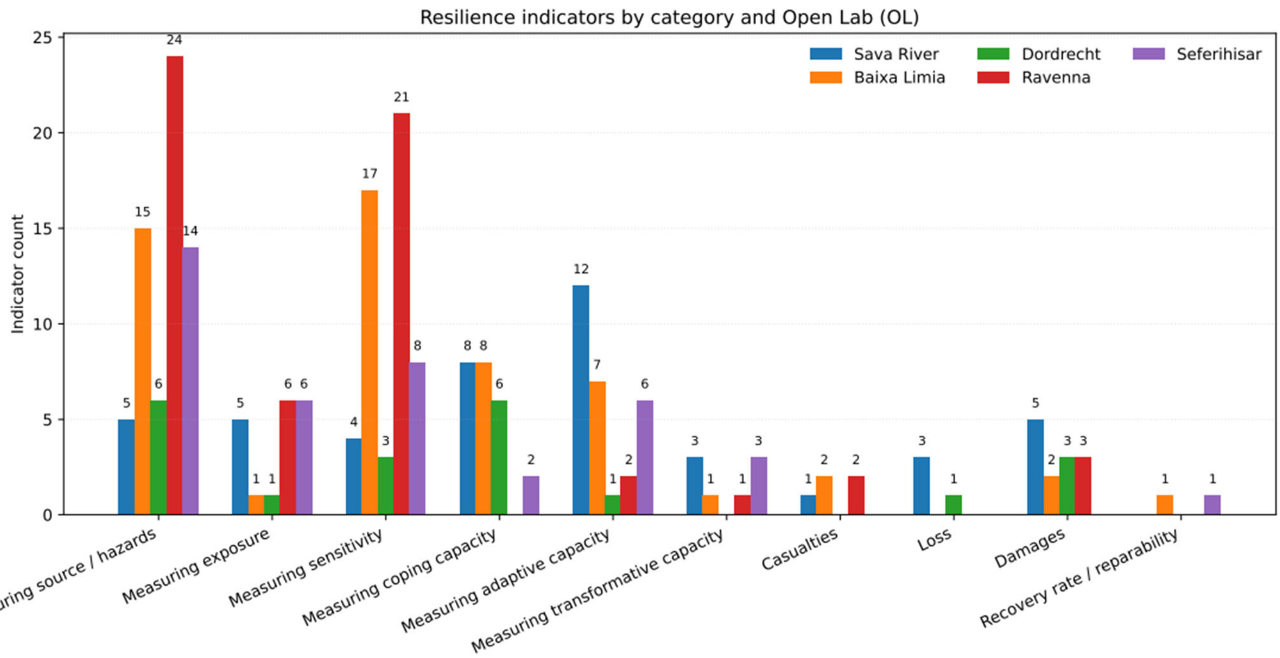

Figure 4. Distribution of resilience indicators selected by five Open Labs across ten measurement categories. Patterns reflect case-specific hazard regimes, governance maturity, and spatial scale.

The number of indicators that the case studies selected as essential and feasible (i.e., indicators that were very important and available) ranged from 21 to 59, representing between 8% and 23% of the overall list of indicators, which seems reasonable in terms of the resilience assessment framework.

4. Discussion

Selections across the five OLs deliberately narrowed the shortlist of 261 indicators to context-appropriate subsets totaling 220, reflecting local relevance and data availability at HA scale. Patterns are consistent with site morphology, hazard regimes, and governance capacity: hazard/source and adaptive objectives are most often represented, whereas transformative capacity and recovery-rate/repairability are least selected.

For hazard/source objectives, selection is, as expected, hazard-dependent. The share chosen by the case studies ranges from 7.2% to 34.8% of the shortlist, with Ravenna (34.8%) and Seferihisar (20.3%) prioritizing hazard characterization, Baixa Limia at 21.7%, Dordrecht at 8.7%, and Sava River at 7.2%. In practice, this indicates that multi-hazard profiling (covering frequency, magnitude, intensity, and duration) is particularly salient for sites facing multiple or intense hazards, and that aligning hazard metrics with maintenance and early-warning practices could be beneficial for HAs without over-prescribing uniform approaches.

Exposure selection aligns with site scale and morphology, with case-study shares between 8.3% and 50.0%. Compact urban HAs emphasize population and buildings (Ravenna 50.0%; Seferihisar 50.0%), while the transnational Sava River Basin distributes exposure across people, activities, and assets (41.7%). These patterns suggest value in maintaining up-to-date asset and population registers and undertaking proportionate exposure audits before major works (ideally integrated with GIS and buffer-zone practices where feasible).

Sensitivity diverges by heritage profile (3.3–23.3%). Natural-heritage-rich contexts weight environmental sensitivity (Baixa Limia 18.9%), whereas urban HAs lean towards building and socio-demographic attributes (Ravenna 23.3%). Periodic vulnerability surveys of heritage fabric and critical infrastructure, complemented by socio-demographic mapping, could therefore provide a balanced basis for prioritizing measures.

In coping capacity, DRM and protection of natural resources are more frequently selected (Sava River 25.8%; Baixa Limia 25.8%), while awareness, networks, and shelter capacity are rarely used, pointing to data gaps and the difficulty of quantifying social processes with publicly available sources. Where resources allow, light-touch community surveys, participatory inventories, or network-mapping exercises could help to generate repeatable indicators of preparedness and social support.

Adaptive capacity shows the highest uptake (4.3–52.2%), led by Sava River (52.2%). Governance/institutional, cultural, and social capital are consistently represented; human and economic capital are less frequently selected, likely reflecting perceived decision-usefulness and public-data availability. This pattern indicates that incremental investments in adaptive governance and in skills and heritage crafts can complement existing strengths, while targeted datasets on human and economic capital may be introduced gradually as they become available.

Despite clear relevance to HAs' intrinsic resilience, transformative capacity is sparsely selected (0.0–37.5%; Sava River and Seferihisar 37.5%, others $\leq$12.5%). Although the research considered the dimension related to transformative capacity, particularly pertinent to HAs and the intrinsic resilience of cultural and natural heritage, case studies selected these indicators less frequently than other categories. Further research is needed to determine whether this stems from the limited maturity or quality of available indicators in a less researched field, or from low awareness or perceived relevance within the case studies. Carefully piloting measurable proxies (for instance, iterative plan updates, participation rates in co-creation, or heritage-compatible innovation projects) may help to build an evidence base over time while guarding against maladaptation.

Recovery indicators are selective. Damage is most tracked (Sava River 41.7%; Dordrecht and Ravenna 25.0%), while casualties and losses appear less often; repairability/recovery rate is scarcely used (Baixa Limia and Seferihisar 20.0%). These results point to the practical value of simple, comparable post-event metrics, such as repairability indices, time-to-reopening, and indirect-loss tracking (tourism, cultural services), that can be adopted progressively and linked to existing recovery practices for HAs.

Overall, indicator selection strongly correlates with the defining characteristics of each case study. Sites with multi-hazard exposure (e.g., Seferihisar) and compact urban morphology (e.g., Ravenna) prioritize hazard characterization and exposure metrics, reflecting the need for granular monitoring of physical triggers and population assets. Conversely, large-scale or transboundary contexts (e.g., Sava River) emphasize adaptive capacity and damage tracking, consistent with governance complexity and the availability of hydrological and spatial datasets. Natural-heritage-rich areas (Baixa Limia) weight environmental sensitivity and coping capacity, while highly institutionalized flood governance (Dordrecht) shows balanced uptake across exposure and adaptive indicators. These patterns confirm that indicator relevance is shaped by hazard regime, spatial scale, heritage profile, governance maturity, and data accessibility, underscoring the importance of tailoring resilience measurement frameworks to local conditions rather than applying uniform prescriptions.

Taken together, the narrower OL selections relative to the shortlist appear appropriate to context and data accessibility at HA scale and still map comprehensively to the SHELTER measurement objectives. To strengthen future assessments, measurement gaps, especially in coping and transformative capacities, may be addressed as data and operational experience accumulate, with greater consistency in data collection and a gradual embedding of indicators into routine governance cycles (planning, budgeting, maintenance, DRM, and recovery). Cultural and natural heritage can be treated as active resilience assets, with proportionate investment in monitoring, skills, and co-management so indicators inform practical decisions, from risk reduction to post-event repair, while safeguarding authenticity.

5. Conclusions

A robust and flexible indicator framework is essential for historic areas (HAs) to design resilience strategies, strengthen disaster risk management (DRM), and evaluate the effectiveness of adaptive measures. Although no universally accepted method exists for measuring resilience, the framework proposed in this paper builds on existing models to propose an integrated, adaptable framework capable of assessing risk and resilience across diverse historical environments.

The SHELTER resilience indicators framework operationalizes risk as a function of hazard, exposure, and vulnerability, including in the latter sensitivity, coping capacity, adaptive capacity, and transformative capacity. By focusing on cultural and natural heritage, the framework captures both hazard-dependent and non-hazard-dependent dimensions of resilience, enabling a multidimensional approach that reflects the intrinsic resilience of HAs. The objective is to provide a quantitative basis for measuring and monitoring the ability of HAs to adapt, cope, and transform in response to hazards.

From a comprehensive state-of-the-art indicator system, this paper proposes a refined selection aligned with HA resilience objectives and based on RACER criteria (relevant, accepted, credible, easy, robust). The resulting framework covers 10 measurement objectives, 43 sub-objectives, and 6 hazard types, offering a multi-scale, multi-hazard approach.

An interactive methodology, tested in five case studies with varying scales, heritage profiles, hazard regimes, and data availability, enabled the prioritization of indicators most relevant to local contexts.

The applicability of the methodology was demonstrated through workshops for stakeholder engagement and consensus-building, confirming its flexibility and practical value. Case studies successfully adapted the indicator system to assess and monitor resilience dimensions, identify strengths and weaknesses, and guide future improvement strategies. However, challenges remain, particularly in data collection, harmonization, and system-level characterization, underscoring the need to treat cultural and natural heritage as sensitive receptors with specific vulnerabilities.

However, the results also reveal important methodological and operational limitations. The reliance on publicly available datasets, while intentional and practical, restricts granularity and can obscure system-level interactions. Moreover, effectiveness depends on sustained stakeholder engagement and institutional continuity, which vary across governance contexts. Moreover, indicator uptake is uneven across dimensions and sites, with coping and transformative capacities under-selected due to limited data availability, immature metrics, and difficulties in operationalizing social and institutional processes at HA scale. Addressing these gaps requires a clearer methodological pathway. First, data strategies should prioritize harmonized, recurrent datasets on preparedness, institutional response, and community awareness, complemented by participatory inputs and improved interoperability between heritage, hazard, and governance records. Second, indicator development should prioritize simplifying and strengthening coping and transformative measures, using RACER-based refinement cycles to enhance clarity and feasibility for stakeholders, and piloting practical, measurable proxies, such as plan-update cycles, training coverage, or heritage-compatible innovation activities. Given the early development stage of these metrics, further research is needed to advance robust, comparable, and operative indicators for coping and especially transformative capacities. Third, operationalization should embed refined indicators into routine governance cycles, with defined update frequencies, verification protocols, and links to decision processes. This pathway will progressively strengthen the evidence base and enhance the ability of historic areas to use indicators as practical tools for risk reduction, adaptive management, and post-event recovery.

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Abbreviations

The following abbreviations are used in this manuscript:

HA	Historic Area
DRM	Disaster Risk Management
CCA	Climate Change Adaptation
CHM	Cultural Heritage Management
IPCC	Intergovernmental Panel on Climate Change
OLs	Open Labs

Appendix A Final List of Indicators

Table A1. Structure and information available in the factsheets. "x" denotes that the indicator is applicable to the specified hazard(s) and scale(s).

ID	P.	Measuring Objective	Subcategory	Indicator	Hazard						Scale			
					Earthquake	**Wildfire**	**Heat waves**	**Storms**	**Floods**	**Subsidence**	**Artefact**	**Building**	**Urban/District**	**Regional**
229	P	Frequency	Hazard characterization	Frequency of disaster event	x	x	x	x	x	x			x	x
6	P		Flood characterization	Flood area corresponding to the return period T					x		x	x	x	x
10	P			Flood frequency: linked with the return period					x		x	x	x	x
344	P		Storm characterization	Number of storms per month				x					x	x
414	P		Wildfire characterization	Fire recurrence		x								x
1	P	Magnitude	Rainfall characterization	Daily maximum precipitation corresponding to the return period T				x	x			x	x	x
2	P			Hourly maximum precipitation corresponding to the return period T				x	x			x	x	x
30	P			Annual precipitation		x							x	x
31	P			Precipitation of wettest month		x							x	x
32	P			Precipitation of driest month		x							x	x

Table A1. *Cont.*

ID	P.	Measuring Objective	Subcategory	Indicator	Hazard						Scale			
					Earthquake	Wildfire	Heat waves	Storms	Floods	Subsidence	Artefact	Building	Urban/District	Regional
33	P	Magnitude	Rainfall characterization	Precipitation seasonality (coefficient of variation)		x							x	x
34	P			Precipitation of wettest quarter		x							x	x
35	P			Precipitation of driest quarter		x							x	x
36	P			Precipitation of warmest quarter		x							x	x
37	P			Precipitation of coldest quarter		x							x	x
19	P		Temperature characterization	Annual mean temperature		x	x						x	x
20	P			Mean diurnal range		x	x						x	x
21	P			Isothermality		x	x						x	x
22	P			Temperature seasonality		x	x						x	x
23	P			Max temperature of warmest month		x	x						x	x
24	P			Min temperature of coldest month		x	x						x	x
25	P			Temperature annual range		x	x						x	x
26	P			Mean temperature of wettest quarter		x	x						x	x
27	P			Mean temperature of driest quarter		x	x						x	x
28	P			Mean temperature of warmest quarter		x	x						x	x
29	P			Mean temperature of coldest quarter		x	x						x	x
43	P			Daily mean temperature			x					x	x	
44	P			Thermal shock			x				x	x	x	
404	P			Annual number of days with Tmin < 0 °C and Tmax > 0 °C				x				x		
415	P			Land surface temperature		x								x

Table A1. *Cont.*

ID	P.	Measuring Objective	Subcategory	Indicator	Hazard						Scale			
					Earthquake	Wildfire	Heat waves	Storms	Floods	Subsidence	Artefact	Building	Urban/District	Regional
46	P	Magnitude	Hygrometric conditions	Mean relative humidity			x					x	x	
47	P			Daily humidity cycle shocks			x				x	x	x	
48	P			Relative humidity concentration			x				x	x	x	
405	P			Daily mean RH inside the building			x	x	x		x	x		
402	P		Wind characterization	Main wind directions in the coldest quarter				x				x	x	
403	P			Main wind directions in the wettest quarter				x				x	x	
11	P		Soil characterization	Surface runoff					x		x	x	x	x
407	P			Ground water table					x	x			x	
15	P		River characterization	Basin response time					x		x	x	x	x
7	P		Flood characterization	Flood depth					x		x	x	x	x
8	P			Water velocity (in the flooded area)					x		x	x	x	x
39	P		Wildfire characterization	Fire weather index		x								x
40	P			Palmer drought severity index		x	x						x	x
45	P		Heat wave characterization	Daily sun hours			x					x	x	
196	P		Subsidence characterization	Subsidence rate					x	x			x	x
396	P			Deflection ratio (relative differential settlement)	x					x		x		
274	P		Storm characterization	Wind speed				x					x	x
281	P			Air pressure				x					x	x
284	P			CAPE index				x				x	x	
332	P			Lifted index				x						x
335	P			Wind pressure				x					x	x
337	P			Gust strength				x					x	x
350	P			Variance of the average wind speed in a defined area per year				x					x	x
351	P			Variance of average gust speeds in defined area per year				x					x	x

Table A1. *Cont.*

ID	P.	Measuring Objective	Subcategory	Indicator	Hazard							Scale		
					Earthquake	Wildfire	Heat waves	Storms	Floods	Subsidence	Artefact	Building	Urban/District	Regional
354	P	Magnitude	Earthquake characterization	Peak ground acceleration (PGA)	x								x	x
355	P			Level of seismic hazard	x								x	x
356	P			Earthquake intensity (modified Mercalli scale)	x								x	x
406	P		Sea-level	Sea level rise					x	x				x
3	P	Intensity	Rainfall characterization	Distribution of the rainfall intensity over time, corresponding to the return period T and the duration of the event				x	x			x	x	x
4	P			Torrentiality index (factor)				x	x			x	x	x
12	P		River characterization	Maximum annual river flow corresponding to the return period T at the drainage point of the basin					x		x	x	x	x
13	P			Maximum annual river level corresponding to the return period T at the drainage point of the basin					x		x	x	x	x
14	P			River basin concentration time					x		x	x	x	x
9	P		Flood characterization	Combinations of flood depth and water velocity in the flood area					x		x	x	x	x
334	P		Storm characterization	Heavy rain				x					x	x
269	P	Duration	Heat wave characterization	Heat wave indicator			x						x	x
343	P		Storm characterization	Storm duration				x					x	x
413	P		Wildfire characterization	Time since fire		x								x
5	P	Intensity, duration, and frequency	Rainfall characterization	IDF (intensity duration frequency) curves				x	x			x	x	x

Table A1. *Cont.*

ID	P.	Measuring Objective	Subcategory	Indicator	Hazard							Scale		
					Earthquake	Wildfire	Heat waves	Storms	Floods	Subsidence	Artefact	Building	Urban/District	Regional
210	P	Individuals	Demographic	Population in hazard area	x	x	x	x	x	x			x	x
213	P	Activities	Hazard area characterization	Productive activities in hazard area	x	x	x	x	x	x			x	x
17	P	Object/buildings/ infrastructure	Infrastructure	Road and traffic disturbance	x	x		x	x	x			x	x
50	P		Building characterization	Daily hillside of roofs			x					x		
51	P			Daily hillside of façades			x					x		
412	P			Vibrations generated on cultural heritage by vehicular traffic	x							x		
54	P		Asset characterization	Sky view factor			x						x	
209	P		Hazard area characterization	Land take in hazard area	x	x	x	x	x	x			x	x
211	P			Buildings in hazard area	x	x	x	x	x	x			x	x
212	P			Critical facilities in hazard area	x	x	x	x	x	x			x	x
57	P	Ecosystems	Pollution	Air quality; near-surface or tropospheric ozone (O_3) levels		x	x						x	x
360	P		Hazard area characterization	Major accident risk factories in hazard area	x	x		x	x	x		x	x	x
58	P	Social/demography characteristics	Demographic	Population density	x	x	x	x	x	x			x	x
89	P			Percentage of population below 65 years of age	x	x	x	x	x	x			x	x
91	P			Percentage of population 17 years of age or younger	x	x	x	x	x	x			x	x
92	P			Percentage population without sensory, physical, or mental disability	x	x	x	x	x	x			x	x
93	P			Percentage of female	x	x	x	x	x	x			x	x
95	P			Percentage of one-person household	x	x	x	x	x	x			x	x
428	P			Total population		x								x

Table A1. *Cont.*

ID	P.	Measuring Objective	Subcategory	Indicator	Hazard						Scale			
					Earthquake	Wildfire	Heat waves	Storms	Floods	Subsidence	Artefact	Building	Urban/District	Regional
429	P	Social/demography characteristics	Demographic	Illiterate population		x								x
161	P			Net international migration	x	x	x	x	x	x			x	x
299	P		Gender equality	Gender-related development index (GDI)	x	x	x	x	x	x				x
111	P	Economic characteristics	Economic	Per capita income	x	x	x	x	x	x			x	x
114	P			Percentage of population above poverty line	x	x	x	x	x	x			x	x
151	P			Unemployment rate	x	x	x	x	x	x			x	x
153	P			Gini coefficient	x	x	x	x	x	x			x	x
156	P			Ratio of large to small businesses	x	x	x	x	x	x			x	x
416	P			Agricultural occupation rate		x								x
417	P		Livestock characterization	Total number of cattle heads		x								x
418	P			Total number of sheep heads		x								x
419	P			Total number of goat heads		x								x
420	P			Total number of poultry heads		x								x
421	P			Total number of swine heads		x								x
422	P			Total number of equine heads		x								x
52	P	Building characteristics	Urban characterization	Albedo			x					x	x	
53	P			Thermal diffusivity			x					x	x	
55	P			Solar reflectance index			x					x	x	
62	P			Year of construction	x	x	x	x	x	x		x		
65	P			Construction material (public space)			x		x				x	
140	P			Percentage of residential buildings	x	x	x	x	x	x		x	x	
150	P			Average annual rate of change in the urban percentage	x	x	x	x	x	x			x	x
181	P			Street pattern	x								x	

Table A1. *Cont.*

ID	P.	Measuring Objective	Subcategory	Indicator	Hazard: Earthquake	Hazard: Wildfire	Hazard: Heat waves	Hazard: Storms	Hazard: Floods	Hazard: Subsidence	Hazard: Artefact	Scale: Building	Scale: Urban/District	Scale: Regional
178	P	Building characteristics	Urban characterization	Building alignment rate	x							x	x	
358	P			New building rate	x								x	x
63	P		Building characterization	State of conservation	x	x	x	x	x	x		x		
67	P			Insulation			x					x		
69	P			Protection level	x	x	x	x	x	x	x	x	x	x
70	P			Structural material	x	x			x	x	x	x		
71	P			Façade material	x	x	x	x	x	x		x		
72	P			Accessible windows	x	x	x	x	x	x		x		
73	P			Fire-resistant sector partitions		x						x		
74	P			Fire-protection installations		x						x		
76	P			Roof material		x	x	x				x		
77	P			Building use/function	x	x	x	x	x	x		x		
80	P			Building typology		x						x		
138	P			Percentage of buildings complying with hazard-resistant building codes and/or standards	x	x	x	x	x	x		x	x	
186	P			Building height	x				x			x	x	
256	P			Percentage of buildings with drainage system in good condition and appropriate dimension					x			x		
257	P			Number of one-floor houses					x			x		
259	P			Percentage of buildings with basement in flood-prone area					x			x		
263	P			Percentage of building with open ground floor or with ground floor above the maximum level of possible flood					x			x		
264	P			Percentage of buildings with structural materials resistant to water penetration					x			x		

Table A1. *Cont.*

ID	P.	Measuring Objective	Subcategory	Indicator	Hazard							Scale		
					Earthquake	Wildfire	Heat waves	Storms	Floods	Subsidence	Artefact	Building	Urban/District	Regional
265	P	Building characteristics	Building characterization	Percentage of buildings with facade materials resistant to water penetration					x			x		
266	P			Number of blue and green roofs					x			x		
267	P			Number of buildings hosting collections with storage capacity in upper floors					x		x	x		
409	P			Site accessibility	x	x		x	x			x		
410	P			Building transformation	x							x		
411	P			Building walls rotations	x							x		
144	P	Infrastructure characteristics	Soil characterization	Yearly average imperviousness change between two reference years		x	x	x	x	x			x	x
390	P		Transport/access	Daily average of transport infrastructure users	x	x	x	x	x	x			x	x
427	P			Road length		x								x
105	P			Distance to service centers	x	x	x	x	x	x			x	
106	P			Distance to fire brigades	x	x	x	x	x	x			x	x
108	P		Communication	Percentage population with a telephone	x	x	x	x	x	x			x	x
109	P			Percentage population with access to broadband internet service	x	x	x	x	x	x			x	x
145	P		Water storage	Dam capacity				x	x	x			x	x
38	P	Environmental sensitivity	Soil characterization	Relative water content in the top few centimeters of soil		x	x						x	x
185	P			Soil water content						x		x	x	
363	P			Soil water index (SWI)		x		x	x				x	x
395	P			Liquefaction potential	x					x		x		

Table A1. *Cont.*

ID	P.	Measuring Objective	Subcategory	Indicator	Hazard						Scale			
					Earthquake	Wildfire	Heat waves	Storms	Floods	Subsidence	Artefact	Building	Urban/District	Regional
59	P	Environmental sensitivity	Pollution	Street noise/acoustic pollution			x						x	
146	P		Land characterization	Average ground slope		x		x	x	x			x	x
180	P			Land taken	x	x		x	x	x			x	x
183	P			Land cover	x		x		x	x			x	x
228	P			Height above sea level					x	x			x	x
366	P		Natural heritage characterization	Number of non-native species of flora introduced		x								x
367	P			Number of non-native faunal species introduced		x								x
368	P			Species diversity within defined area per Shannon diversity index		x								x
369	P			Number of species within defined area per Shannon evenness index		x								x
372	P			Extent of habitat for native pollinator species		x								x
373	P			Proportion of natural areas within a defined zone		x							x	x
374	P			Number of conservation priority species		x								x
375	P			Number of native/local provenance species		x								x
376	P			Number of native bird species within a defined urban area		x							x	x
377	P			Change in number of native species compared to a baseline number of species		x								x
380	P			Shannon index		x								x
382	P			Plant/root decay rate		x								x

Table A1. *Cont.*

ID	P.	Measuring Objective	Subcategory	Indicator	Hazard						Scale			
					Earthquake	Wildfire	Heat waves	Storms	Floods	Subsidence	Artefact	Building	Urban/District	Regional
423	P	Environmental sensitivity	Natural heritage characterization	Landscape heterogeneity		x								x
425	P			Beta diversity		x								x
426	P			Functional diversity		x								x
370	P		Wildfire characterization: fuel accumulation	Number of veteran trees per unit area		x		x						x
371	P			Quantity of dead wood per unit area		x								x
84	P	Awareness/ information	Education	Percentage of population with access to risk information	x	x	x	x	x	x			x	x
188	P		Social capital	Risk perception	x	x	x	x	x	x			x	x
190	P		Infrastructure	Infrastructure redundancy	x								x	
278	P		Communication	Media observation for public pressure	x	x	x	x	x	x			x	x
313	P		Community preparedness	Public information and community participation	x	x	x	x	x	x				x
353	P		Institutional	Count of missions due to storm events				x					x	x
245	P	Networks/ solidarity/ community preparedness	Community preparedness	Number of measures taken by individuals to reduce damage	x	x	x	x	x	x		x	x	
124	P	Insurance/funds	Governance and finance	Infrastructure and housing insurance as a percent of GDP	x	x	x	x	x	x			x	x
330	P			Existence of social safety nets and funds	x	x	x	x	x	x				x
331	P			Insurance coverage and loss transfer strategies for public assets	x	x	x	x	x	x				x
172	P	DRM	Institutional	Ten-year average per capita spending for mitigation projects	x	x	x	x	x	x			x	x
223	P			Coordination with other government bodies	x	x	x	x	x	x			x	x

Table A1. *Cont.*

ID	P.	Measuring Objective	Subcategory	Indicator	Hazard						Scale			
					Earthquake	Wildfire	Heat waves	Storms	Floods	Subsidence	Artefact	Building	Urban/District	Regional
321	P	DRM	Institutional	Organization and coordination of emergency operations	x	x	x	x	x	x			x	x
248	P		Risk identification	Prediction capacity	x	x	x	x	x	x			x	x
310	P			Hazard monitoring and forecasting	x	x	x	x	x	x				x
311	P			Hazard assessment and mapping	x	x	x	x	x	x			x	x
312	P			Vulnerability, risk assessment, and mapping	x	x	x	x	x	x		x	x	x
322	P		Response	Emergency response planning and implementation of warning systems	x	x	x	x	x	x			x	x
326	P		Recovery	Rehabilitation and reconstruction planning	x	x	x	x	x	x		x	x	x
130	P	Shelter capacity	Infrastructure	Hotels/motels per 10,000 persons	x	x	x	x	x	x			x	x
56	P	Protection of natural resources	Ecological capacity	Vegetation density (NDVI)		x	x						x	x
149	P			Share of ecological corridors		x		x	x	x			x	x
364	P			Structural connectivity of green infrastructure		x							x	x
365	P			Functional connectivity of green infrastructure		x								x
378	P			Area of habitats restored		x								x
379	P			Habitat functional composition (relative abundance of functional features)		x								x
381	P			Urban green space proportion		x		x					x	
424	P			Vegetation water content		x								x
430	P			Habitat-suitability index under climate change scenarios		x								x

Table A1. *Cont.*

ID	P.	Measuring Objective	Subcategory	Indicator	Hazard						Scale			
					Earthquake	Wildfire	Heat waves	Storms	Floods	Subsidence	Artefact	Building	Urban/District	Regional
148	P	Protection of natural resources	Ecological capacity	Share of the protected lands		x		x	x	x			x	x
316	P		Risk reduction	Management of river basins and environmental protection		x		x	x					x
83	P	Human capital/education	Education	Number of participants in training courses executed by authorities, institutions, corporations, or other bodies, specific for DRM	x	x	x	x	x	x			x	x
384	P		Training	Number of professionals trained in post-disaster recovery and preservation of cultural heritage	x	x	x	x	x	x	x	x	x	x
126	P	Social capital/learning	Infrastructure	Psychosocial support facilities per 10,000 persons	x	x	x	x	x	x			x	x
165	P		Social capital	Civic organizations per 10,000 persons	x	x	x	x	x	x			x	x
166	P			Red cross volunteers per 10,000 persons	x	x	x	x	x	x			x	x
169	P			Budget of volunteer organizations	x	x	x	x	x	x			x	x
170	P			Number of registered volunteers	x	x	x	x	x	x			x	x
218	P		Institutional	People with access to emergency medical care	x	x	x	x	x	x			x	x
158	P	Economic capital	Activities	Percentage of firms implementing international risk management standards in the organization structure and processes	x	x	x	x	x	x			x	x
287	P		Economic	Economic resilience index adapted based on disaster deficit index	x	x		x	x					x

Table A1. *Cont.*

ID	P.	Measuring Objective	Subcategory	Indicator	Hazard						Scale			
					Earthquake	Wildfire	Heat waves	Storms	Floods	Subsidence	Artefact	Building	Urban/District	Regional
174	P	Institutional capital/governance	Institutional	Percentage population covered by a mitigation plan	x	x	x	x	x	x			x	x
226	P			Mechanisms for communities to engage with government	x	x	x	x	x	x			x	x
315	P			The extent to which risk is taken into account in land use and urban planning	x	x	x	x	x	x			x	x
329	P		Economic	Budget allocation and mobilization	x	x	x	x	x	x			x	x
241	P	Cultural capital/identity	Cultural capital	Intangible value of cultural and natural heritage	x	x	x	x	x	x		x	x	x
242	P			Presence of a traditional culture	x	x	x	x	x	x	x	x	x	x
129	P	Built capital/infrastructure	Infrastructure	Hospital beds per 10,000 persons	x	x	x	x	x	x			x	x
250	P		Equipment	Available (collective) equipment to limit damage		x			x			x	x	x
323	P			Supply of equipment, tools, and infrastructure	x	x	x	x	x	x			x	x
320	P		Building characterization	Reinforcement and retrofitting of public and private assets	x	x	x	x	x	x		x	x	x
389	P		Equipment	Percentage of existing primary infrastructures provided with back-up systems	x	x	x	x	x	x			x	x
397	P	Natural capital	Ecological capacity	Area under vegetation and wetlands		x	x	x	x					x
431	P			Total carbon sequestered and carbon sequestration rate		x								x

Table A1. *Cont.*

ID	P.	Measuring Objective	Subcategory	Indicator	Hazard						Scale			
					Earthquake	Wildfire	Heat waves	Storms	Floods	Subsidence	Artefact	Building	Urban/District	Regional
398	P	Social memory/living with uncertainty/improvising	Local knowledge	Existence of mechanisms for integration local knowledge and local perceptions of risk and scientific knowledge, data, and assessment methods	x	x	x	x	x	x			x	x
399	P		Communication	Existence of a platform for information sharing and networking using tools and routines and number of unique users	x	x	x	x	x	x			x	x
327	P	Self-organization; reflective and shared learning	Institutional	Decentralized organizational units; inter-institutional and multisector coordination	x	x	x	x	x	x			x	x
328	P	Resourcefulness/efficiency	Institutional	Availability of resources for institutional strengthening	x	x	x	x	x	x			x	x
324	P	Collaboration/inclusive/diversity/intersectoriality	Institutional	Simulation, updating, and testing of inter-institutional response capability	x	x	x	x	x	x			x	x
319	P	Robustness/strength/appropriately connected	Risk reduction	Updating and enforcement of safety standards and construction codes	x	x	x	x	x	x		x	x	x
400	P	Innovation	Activities	Number of new businesses registered within the area in the past year, per 100,000 population	x	x	x	x	x	x			x	x
401	P	Coupled with local Natural capital	Energy	Percentage of renewable energy	x	x	x	x	x	x			x	x
204	R	Casualties	Individuals	Number of fatalities	x	x	x	x	x	x			x	x
205	R			Number of non-fatal injuries	x	x	x	x	x	x			x	x
271	R			Compared mortality	x	x	x	x	x	x			x	x

Table A1. *Cont.*

ID	P.	Measuring Objective	Subcategory	Indicator	Hazard: Earthquake	Hazard: Wildfire	Hazard: Heat waves	Hazard: Storms	Hazard: Floods	Hazard: Subsidence	Scale: Artefact	Scale: Building	Scale: Urban/District	Scale: Regional
272	R	Casualties	Individuals	Increased hospitalization	x	x	x	x	x	x			x	x
273	R	Economic loss	Individuals	Stays in hospitals	x	x	x	x	x	x			x	x
277	R			Reduced working capacity	x	x	x	x	x	x			x	x
309	R		Institutional	Systematic inventory of hazard events, damage, and losses	x	x	x	x	x	x				x
347	R		Finance	Reported insurance claims	x	x	x	x	x	x			x	x
383	R		Damage characterization	Direct economic loss to cultural heritage damaged or destroyed	x	x	x	x	x	x	x	x	x	x
385	R	Indirect loss	Damage characterization	Affected intangible cultural heritage	x	x	x	x	x	x		x	x	x
387	R		Individuals	Number of people displaced or forced to relocate	x	x		x	x	x		x	x	x
206	R	Damage in buildings	Damage characterization	Number of collapsed or heavily damaged buildings	x	x		x	x	x		x	x	x
207	R			Affected critical facilities	x	x	x	x	x	x		x	x	x
232	R			Stage damage curve, direct impacts	x	x	x	x	x	x		x	x	x
348	R			Slight or moderate damaged buildings	x	x	x	x	x	x		x	x	x
432	R			Biological colonization			x	x	x		x	x		
349	R	Damage in ecosystem	Damage characterization	Windthrow in defined area				x					x	x
394	R			Loss of ancestral land and natural heritage	x	x	x	x	x	x				x
408	R			Burn severity index		x								x
386	R			Loss of habitat and biodiversity	x	x		x	x					x
388	R	Damage in infrastructure	Damage characterization	Duration of infrastructure outage	x	x	x	x	x	x		x	x	x
392	R	Damage in objects	Damage characterization	Slight or moderate damaged movable heritage	x	x	x	x	x	x	x			

Table A1. *Cont.*

ID	P.	Measuring Objective	Subcategory	Indicator	Hazard						Scale			
					Earthquake	Wildfire	Heat waves	Storms	Floods	Subsidence	Artefact	Building	Urban/District	Regional
393	R	Damage in objects	Damage characterization	Heavily damaged movable heritage	x	x	x	x	x	x	x			
233	R	Recovery rate	Recovery	Recovery rate	x	x	x	x	x	x	x	x	x	x
352	R		Institutional	Operating hours due to storm events				x					x	x
391	R		Ecological capacity	Vegetation recovery rate	x	x		x	x	x				x
433	R			Primary productivity (EVI/NDVI time series): biomass/species' habitat/post-fire recovery rates		x								x
234	R	Reparability	Reparability	Repairability	x	x	x	x	x	x	x	x	x	x

Appendix B Structure of the Factsheets

DESCRIPTION	
Id	Identification number of the indicator
Name	Denomination of the indicator
Phase	Phase to which the indicator applies: prevention or recovery
Hazard	Identifies the hazards related to the indicator: earthquake, flood, storm, heatwave, wildfire, subsidence
Objective	Risk component the indicator is measuring
Type	Descriptive/assessment/monitoring
Scale	Artefact/building/urban/district/regional
Definition	Definition of the indicator
fFcus/objectives	Subcategory
CH singularity	Is it an indicator specifically addressing cultural and/or natural heritage?
Notes	
Data and measurement	Data sources and measurement unit
Required data	Required data for the calculation of the indicator
Complexity level	• Easy to calculate and requires few data • Easy to calculate but requires data • Medium calculation difficulty and required data • Medium calculation difficulty but requires a lot of data • High calculation and requires few data • High calculation difficulty and requires a lot of data

Input type	Quantitative/qualitative
Data source	Data sources for the calculation
Frequency	How often to use this indicator (hourly, daily, monthly, seasonal, yearly. . .)
Measurement unit	Professionals
Required tool	If specific tools/software are needed for the calculation of the indicator
Calculation method	How the indicator is calculated through a formula or a detailed description on how to obtain it
Output type	Quantitative/qualitative
Examples	
Links and references	
Keywords	

Appendix C Extended Comparative Analysis of Resilience Models and Their Integration Within the Measuring Objectives of SHELTER Framework

Source	**Elements of resilience**								
SPRC	Source	Pathway	Receptor					Consequences	
SPRC EXT.	Source	Pathway	Receptor				Measures	Consequences	Recovery
IPCC/SREX	Risk						Development		
	Hazard	Exposure	Vulnerability						
			Sensitivity		Adaptative capacity		DRM CCA		
		Environmental dimension (including urban environment)							
		Social dimensions (incl. demography, education, governance, cultural. . .)							
		Economic dimension							
DPSIR		Source						Impacts	Response
DRIB		Exposure		Vulnerability					
			Susceptibility	Coping capacity	Adaptative capacity				
PAR				Risk					
	Hazard			Vulnerability					
		Root causes	Dynamic pressures	Unsafe conditions					
EEA				Coping	Incremental adaptation	Transformational adaptation			
SHELTER				**Risk**			**Measures**	**Consequences**	**Recovery**
				vulnerability			DRM CCA CHM	Casualties	Recovery rate
	Hazard/source	Exposure/pathaway	Sensitivity	Coping capacity	Adaptative capacity	Transformative capacity/inherent resilience	Reducing exposure	Indirect loss	Reparability
	Frequency	Individuals	Social/demography characteristics	Awareness/information	Human capital/education	Social memory/living with uncertainty	Reducing sensitivity	Economic loss	
	Magnitude	Community	Economic characteristics	Networks/solidarity/community preparedness	Social capital/learning	Self-organization; reflective and shared learning	Increasing coping capacity	Indirect loss	

	Duration	Processes	Building /infrastructure	Insurance/ funds	Economic capital	Resourcefulness/ efficiency	Increasing adaptive capacity	Damage in buildings/ infrastructure/ objects
		Activities	Environmental sensitivity	DRM	Institutional capital/ governance	Collaboration/ inclusive/diversity/ intersectoriality	Increasing transformative capacity	Ecosystems
SHELTER		Object/ buildings/ infrastructure		Social memory	Cultural capital/identity	Innovation		
		Ecosystems		Shelter capacity	Built capital/ infrastructure	Robustness/strength/ appropriately connected		
				Protection of natural resources	Natural capital	Coupled with local natural capital		

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