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ARTICLE

# A Methodology for Vulnerability Assessment of Cultural Heritage in Extreme Climate Changes

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**Abstract**
Vulnerability evaluation plays a key role in risk assessment and reduction and is essential for defining strategies for climate change adaptation and mitigation. In dealing with the safeguarding of cultural heritage at risk, we are still far from adopting and applying an agreed methodology for vulnerability assessment. With the aim to support practitioners, heritage managers, and policy and decision makers to undertake actions that address the protection of cultural heritage at risk, the methodology set up in the framework of the Interreg Central Europe STRENCH is illustrated and discussed here. Based on three major requirements (susceptibility, exposure, and resilience) and a continuous consultation with local stakeholders, the proposed methodology is applicable for evaluating the vulnerability of built heritage and cultural landscape exposed to hydrometeorological hazards, such as heavy rains, floods, and droughts. The results obtained through its validation on 15 case studies from seven Central European regions are shown to underline the strengths and limitations of the methodological approach. Iterative consultation with local stakeholders was fundamental for the definition of the criteria/subcriteria and related values for the assessment of the requirements. Application to further sites in other contexts would surely contribute to strengthening the reliability of the methodological approach.

**Keywords** Built and natural heritage · Exposure · Heritage vulnerability · Resilience · Risk management · Susceptibility

## 1 Introduction

Nowadays, developing tailored strategies for managing and reducing risk from climate-influenced hazards for cultural heritage has become core to policy and decision making (European Commission 2022). Such interest has been strongly driven by significant research advancements achieved in the last decades, in particular those concerning the evaluation of the impact of ongoing and extreme variations of climate parameters on the built heritage and cultural landscape. Considerable research has mainly defined future damage projections on specific heritage materials caused by ongoing changes in temperature, relative humidity, and precipitation (Bonazza and Sardella 2023).

More recently, several research projects at the European level have been dedicated to risk assessment of heritage assets subjected to disasters and extreme changes in climate—examples are H2020 STORM, HERACLES, SHELTER, HYPERION, and ARCH; and JPI CH PROTHEGO, and Interreg Central Europe ProteCHt2save and STRENCH. Different methodological approaches based on the interactions between hazards, exposure, and vulnerability have been investigated (Reimman et al. 2018; Appiotti et al. 2020; Rosa et al. 2021; Valagussa et al. 2021; IPCC 2022; Egusquiza et al. 2023), with the specific intent to tackle the challenges posed by the impact of climate extremes (for example heavy rain, flooding, drought) on cultural heritage. In most of these methodologies, the hazard analysis has been carried out by selecting and elaborating adequate indices of extreme climate and by finally applying regional climate models that allow the mapping at a spatial resolution of 12 × 12 km in the near (2021–2050) and far future (2071–2100) (Sardella et al. 2020; Kotova et al. 2023).

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Several other approaches have been concentrated instead on vulnerability assessment. Vulnerability evaluation plays a key role in risk assessment and reduction and represents a prerequisite for developing proper strategies for climate change adaptation and mitigation with benefits to cultural heritage (Jigyasu et al. 2013; Sesana et al. 2020; Cacciotti et al. 2021; Cardona et al. 2012; Briz et al. 2023; Ravan et al. 2023). Despite the considerable volume of research conducted, controversy remains regarding vulnerability assessment, particularly when dealing with cultural heritage protection under climate change. For example, the definition of the domains involved (environmental, physical-chemical, sociocultural, economic, and so on), as well as the selection of the assessment criteria (and their weights) to determine vulnerability, are still debated (Tapsell et al. 2010; Roders 2013; Gandini et al. 2020). Despite the efforts to parametrize and rank vulnerability, the current situation is still far from adopting a commonly established methodological approach. The continuing lack of a widely agreed definition of vulnerability (Birkmann 2006; Thywissen 2006; Bonazza et al. 2021; Moreira et al. 2021; Gaddi et al. 2022) disables the clear representation of the problem opening up to heterogeneous interpretation. Moreover, several studies highlight its multi-dimensional (Tapsell et al. 2010), dynamic, scale-dependent (Figuereido et al. 2020), and site-specific variability (Figuereido et al. 2021).

This study aimed to provide a validated methodology for evaluating and ranking the vulnerability of built and natural heritage assets (for example, cultural landscapes, ruined hamlets, parks, and gardens), subjected to potential impact of specific hydrometeorological hazards, such as floods (flash and large basin), landslides, windstorms, and fires linked to droughts. Developed within the framework of the project Interreg Central Europe STRENCH,[1] the methodology has been applied to 15 case studies located in seven different European regions.

## 2 Assessing Vulnerability of Cultural Heritage Under Climate Change Scenarios: Conceptual Framework and Methodological Approach

The development of a functional and effective vulnerability assessment methodology requires the preliminary establishment of systematic frameworks able to integrate heterogeneous vulnerability-related information. This step facilitates a structured, understandable, and defensible decision-making process based on an optimized use of the available resources.

[1] https://programme2014-20.interreg-central.eu/Content.Node/STRENCH.html

Multi-criteria decision-making (MCDM), also known as multiple-criteria decision analysis (MCDA), represents a powerful tool capable of synthesizing complex considerations to evaluate and prioritize different alternatives (Cinelli et al. 2014). Among the several multi-criteria methodologies developed over time (Sadok et al. 2009; Wang et al. 2009; Huang et al. 2011; Herva and Roca 2013), the MIVES (Spanish acronym: Modelo Integrado de Valor para una Evaluacion Sostenible, in English: Integrated Value Model for Sustainability Assessment) (Boix-Cots et al. 2022) stands out for its high adaptation capacity. It is based on multi-attribute utility theory (MAUT) and analytical hierarchy process (AHP, Saaty and Kearns 1985) combining different features, such as a multi-level requirement aggregation framework, the inclusion of a weighting process, and the use of indicator value utility functions. This tool enables structuring the problem within a multi-criteria analysis framework in which different alternatives can be evaluated according to a pre-established set of requirements to satisfy a pre-defined objective. These requirements contain sets of criteria that, in turn, contain a set of indicators and possibly subindicators, thus creating a multi-level system. The requirement tree is a hierarchical diagram in which the various characteristics of the processes to be evaluated are defined in an organized manner.

The MIVES considers three different levels: requirements, criteria, and indicators (subcriteria). In the first two levels, general and qualitative aspects are defined, while in the last level—the indicators, concrete and measurable aspects, are considered. Requirements and criteria have the objective of representing what is needed to evaluate, avoiding the repetition of certain aspects or avoiding the use of aspects that are out of scope. Indicators (subcriteria) should be representative, differentiating, complementary, relative, quantifiable, and traceable. The tree must have a minimum number of indicators independent of each other, to ensure that, together with the assigned weights, it offers a reliable assessment scenario.

As outlined in the literature (Pons et al. 2016), the MIVES approach is implemented by: (1) problem definition; (2) drafting decision model with variables; (3) introducing value functions for normalization of variables; (4) assigning weights; (5) identifying solutions to problem set in step 1; (6) employing model to assess solutions; and (7) decision making by choosing an appropriate solution.

The methodology proposed in this study exploits the effectiveness of the MIVES multi-criteria analysis framework, adjusting it to the scope of cultural heritage vulnerability evaluation. First, vulnerability is understood as a function of three main factors, that is, the so-called requirements: susceptibility, exposure, and resilience. Each factor identifies a set of conditions of a cultural heritage system

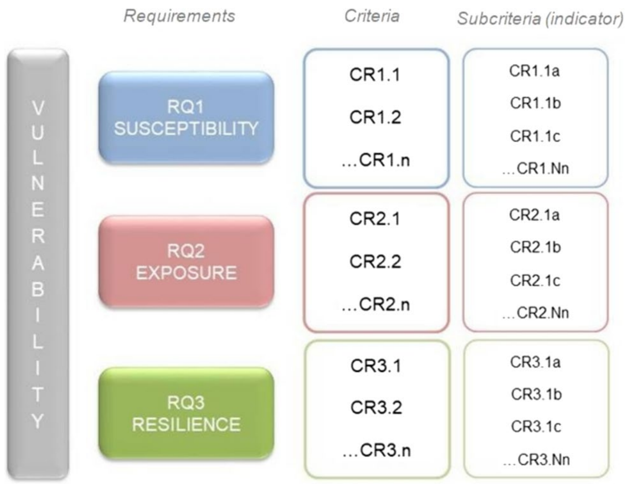


**Fig. 1** Proposed vulnerability framework based on the integrated value model for sustainability assessment (MIVES). *RQ* Requirement, *CR* Criterion

that makes it vulnerable, that is, prone to experience damage under specific disaster scenarios.

Susceptibility or sensitivity refers to the physical characteristics of the system under analysis and it reflects the performance of its structural and material features to withstand the effects of natural hazards (Ravan et al. 2023). As defined by the United Nations Office for Disaster Risk Reduction (UNDRR 2016), exposure represents the conditions "of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas" (UNDRR 2016) (for example, the number of people, monetary value of assets, livelihoods, and so on). Resilience identifies "the ability of a system exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management" (UNDRR 2016). Hence, susceptibility, exposure, and resilience constitute the first layer of the proposed framework (Fig. 1).

As mentioned, different definitions of vulnerability are available in the literature depending on the specific scope of the study. The assessment methodology we proposed stems from the conceptual framework provided by Turner or Balica, which illustrates vulnerability as a function of exposure, sensitivity, and resilience (Turner et al. 2003; Balica et al. 2012).

Therefore, it should be underlined that in this study, exposure is considered an integral part of vulnerability, rather than an external factor that together with vulnerability and hazard compose risk. This choice is governed by the very conceptualization of exposure, which identifies those conditions of the system that determine "the degree to which a system is susceptible and unable to cope with adverse effects of disasters" (IPCC 2022). This is in line with the double-structure conceptual framework of vulnerability provided by Bohle (2001), which also clearly intends exposure to hazards and shocks as a key component of vulnerability itself (Birkman et al. 2006).

Second, as shown in Fig. 1, in addition to the requirement level, the proposed framework considers two deeper stages of analysis, namely the criteria level and the indicators (or more precisely subcriteria). Both levels identify relevant aspects of built and natural heritage vulnerability. Susceptibility, exposure, and resilience criteria and subcriteria frameworks are further discussed in the sections below. The methodology, in addition, provides weights for requirements, criteria, and subcriteria (that is, $\gamma_{RQ}$, $\gamma_c$, and $\gamma_{sc}$ in Tables 1, 2, 3) and evaluation scales (Tables 7, 8, 9), determined by exploiting existing knowledge available in the literature (see Sects. 2.1, 2.2, and 2.3), then employing participatory ranking techniques (Satay and Kearns 1985). More specifically, weighting is carried out by analyzing criteria at the same level of the requirements tree. Weights are then further adjusted following experts' opinion and modeling requirements set by stakeholders responsible for the case studies investigated in this study. Adjustments are made iteratively, following the testing phase of the model. The aggregation of values into a vulnerability index is based on the additive method, as in Munyai et al. (2019). Exposure and susceptibility positively influence vulnerability, whereas resilience negatively influences vulnerability, therefore it can be evaluated as follows:

$$\text{Vulnerability} = \text{Exposure} + \text{Susceptibility} - \text{Resilience} \quad (1)$$

Physical vulnerability is mainly considered. Consequently, susceptibility criteria relate primarily to that dimension. As far as the exposure is concerned, the cultural aspect is given a leading role in the model. However, the socioeconomic dimensions are also introduced in order to take into consideration the remarkable contribution they provide to vulnerability evaluation. It should be noted that the proposed weighting may vary due to site specificity (for example, typology of cultural heritage, hazard at cultural heritage, and son on). Therefore, the weights and evaluation scales presented in this work are specifically validated for the scenarios tested and may need further adjustments for other applications. In addition, situations of multiple simultaneous risks and synergic effects among concurring climate-related actions are not specifically addressed by the proposed methodology, and require a thorough investigation in future studies.

**Table 1** List of selected susceptibility criteria and subcriteria from the literature for flood, flash flood, landslide, windstorm, and fire

| Requirement | Susceptibility (RQ1) | $\gamma_{RQ1}$ = 0.70 | |
|---|---|---|---|
| Criterion | Subcriterion | $\gamma_c$ | $\gamma_{sc}$ |
| CR1.1 Buildings | CR1.1a Constructions and materials | 0.20 | 0.50 |
| | CR1.1b Use | | 0.10 |
| | CR1.1c State of conservation | | 0.20 |
| | CR1.1d Previous harming interventions | | 0.20 |
| CR1.2 Built/human-made features | CR1.2a Built elements of decoration | 0.15 | 0.20 |
| | CR1.2b Water features | | 0.20 |
| | CR1.2c Circulation features | | 0.20 |
| | CR1.2d State of conservation | | 0.40 |
| CR1.3 Vegetation | CR1.3a1 Species (Tree) | 0.35 | 0.40 (0.25) |
| | CR1.3a2 Age (Tree) | | 0.30 (0.25) |
| | CR1.3a3 Slenderness ratio (Tree) | | 0.30 (0.25) |
| | CR1.3b Grass/shrub cover | | 0.25 |
| | CR1.3c Use | | 0.25 |
| | CR1.3d State of conservation | | 0.25 |
| CR1.4 Topography | – | 0.10 | |
| CR1.5 Geosphere | CR1.5a Bedrock | 0.10 | 0.30 |
| | CR1.5b Soil | | 0.50 |
| | CR1.5c Geomorphology | | 0.20 |
| CR1.6 Hydrosphere | CR1.6a Groundwater | 0.10 | 0.30 |
| | CR1.6b Surface water | | 0.40 |
| | CR1.6c Sea | | 0.30 |

**Table 2** List of selected exposure criteria and subcriteria from the literature for flood, flash flood, landslide, windstorm, and fire

| Requirement | Exposure (RQ2) | $\gamma_{RQ2}$=0.30 | |
|---|---|---|---|
| Criterion | Subcriterion | $\gamma_c$ | $\gamma_{sc}$ |
| CR2.1 Cultural significance | CR2.1a Built systems and features | 0.40 | 0.25 |
| | CR2.1b Natural systems and biodiversity | | 0.25 |
| | CR2.1c Cultural traditions | | 0.20 |
| | CR2.1d Cultural acknowledgments | | 0.30 |
| CR2.2 Population | – | 0.20 | – |
| CR2.3 Economic | – | 0.20 | – |
| CR2.4 Infrastructure | – | 0.20 | – |

**Table 3** List of selected resilience criteria and subcriteria from literature for flood, flash flood, landslide, windstorm, and fire

| Requirement | Resilience (RQ3) | $\gamma_{RQ3}$=0.30 | |
|---|---|---|---|
| Criterion | Subcriterion | $\gamma_c$ | $\gamma_{sc}$ |
| CR3.1 Preparedness capacity | CR3.1a Maintenance | 0.50 | 0.30 |
| | CR3.1b Warning | | 0.20 |
| | CR3.1c Knowledge and awareness | | 0.20 |
| | CR3.1d Information | | 0.15 |
| | CR3.1e Policy and regulation | | 0.15 |
| CR3.2 Coping capacity | CR3.2a Emergency resources | 0.25 | 0.40 |
| | CR3.2b Mitigating systems/measures | | 0.30 |
| | CR3.2c Physical strengthening/protection | | 0.30 |
| CR3.3 Restorative capacity | CR3.3a Financial recovery | 0.25 | 0.30 |
| | CR3.3b Social recovery | | 0.30 |
| | CR3.3c Physical recovery | | 0.40 |

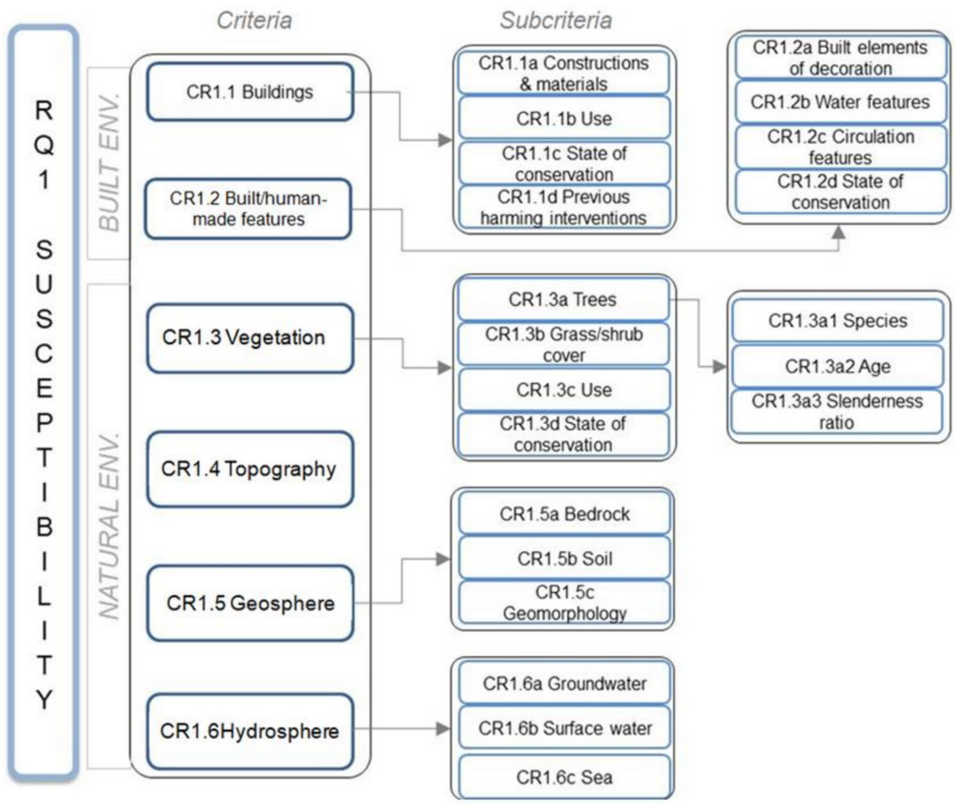


**Fig. 2** Susceptibility criteria and subcriteria. *RQ* Requirement, *CR* Criterion

## 2.1 Susceptibility

The susceptibility requirement (RQ1) is modeled as presented in Fig. 2. Two main criteria groups are considered: the built environment (CR1.1 and CR1.2) group and the natural environment group (CR1.3–CR1.6). Each criterion can be defined as follows:

- CR1.1) Constructions present on-site, including buildings. The characteristics of the construction considered strongly affect its behavior if impacted by climate action. This criterion is divided into the following subcriteria:
  - CR1.1a construction typology and materials' susceptibility to damage;
  - CR1.1b use status (abandoned, continuous, and so on);
  - CR1.1c current status of the object's conservation;
  - CR1.1d past interventions negatively affecting the building (additions, incompatible materials, and so on).
- CR1.2) Built/human-made features include ancillary artefacts that are used for decoration or functional reasons. Subcriteria include:
  - CR1.2a built elements of decoration: obelisks, columns, romantic ruins, ornamental gates, statues, and so on, benches and other seats, hydraulic artefacts (wells, cisterns, paved drains, and so on).
  - CR1.2b water features: pools, canals, rills, fountains, and cascades.
  - CR1.2c circulation features: walls, bridges, paths, entrance lodges. These include also edges: perimeter walls, retaining walls, biotic/abiotic hedges, and so on.
  - CR1.2d state of conservation.
- CR1.3) Vegetation including trees, shrubs, and grass cover. Subcriteria include:
  - CR1.3a trees (species, age, and slenderness ratio);
  - CR1.3b shrub/grass cover;
  - CR1.3c land use;
  - CR1.3d current status of the object's conservation.
- CR1.4) Topography of the site (for example, altitude, slope characteristics, and so on).
- CR1.5) Geosphere. Subcriteria include:
  - CR1.5a bedrock properties;

- CR1.5b soil properties (for example, sand, gravel, clay);
- CR1.5c geomorphologic features of the site (geological formation, and so on).

- CR1.6) Hydrosphere. Subcriteria include:
  - CR1.6a groundwater;
  - CR1.6b surface water;
  - CR1.6c sea.

Table 1 presents the selected susceptibility variables referred to as criteria and subcriteria and factors $\gamma_{RQ1}$, $\gamma_c$, and $\gamma_{sc}$ indicating the weight assigned to respectively RQ1 (susceptibility), criteria, and subcriteria, adjusted from available literature (for example, Gandini et al. (2018); Papathoma-Köhle et al. (2019), and Malgwi et al. (2020)).

Susceptibility can be calculated as the weighted sum of all subcriteria factorized by the criterion's coefficient $\gamma_c$, using the formula:

$$RQ1 = \sum_{i=1}^{6} \gamma_{c,i} \left( \sum_{m=1}^{n} (value) \gamma_{sc,m} \right) \quad (2)$$

where $n$ is the number of subcriteria belonging to the specific criterion and *value* is the score assigned to each subcriterion according to evaluation scales set in Table 4.

## 2.2 Exposure

The criteria taken into consideration for the assessment of the exposure of cultural heritage include the cultural significance criterion, evaluating identifiable tangible and intangible attributes of the asset, as well as socioeconomic criteria, which are essential in the vulnerability assessment of cultural heritage (Fig. 3).

The criteria proposed for the modeling of the exposure are:

- CR2.1) Cultural significance, which involves the characterization of the subcriteria:
  - CR2.1a built systems and features (for example, small-scale features such as benches, fences, monuments, road markers, flagpoles, signs, foot bridges, curbstones, trail ruts, culverts, and foundations);
  - CR2.1b natural systems and features (for example, views and vistas such as a lookout structure or a view framed by vegetation);
  - CR2.1c cultural traditions, which involves those practices that have impacted the development of land use, building forms, stylistic preferences, and the use of materials;
  - CR2.1d cultural acknowledgments (for example, formal legal protection status).

Movable heritage assets, such as paintings, books, and artworks, often found in heritage buildings and sites, can be modeled in the presented framework as exposure (that is, additional value), which should be considered in the evaluation of CR2.1.

- CR2.2) Population (for example, livelihoods, density, demographic properties).
- CR2.3) Economic (for example, real estate value, commercial value, income production).
- CR2.4) Infrastructure (for example, communication or transport networks).

Table 2 presents the selected exposure criteria and subcriteria. Factors $\gamma_{RQ2}$, $\gamma_c$, and $\gamma_{sc}$ refer to the weight assigned to respectively RQ2 (exposure), criteria, and subcriteria, determined by adjusting existing knowledge available in the literature (Roders 2013; Proag 2014; Melnick and Kerr 2018).

Similar to susceptibility, exposure can be calculated as the weighted sum of all subcriteria factorized by the criterion's coefficient $\gamma_c$, as follows:

$$RQ2 = \sum_{i=1}^{4} \gamma_{c,i} \left( \sum_{m=1}^{n} (value) \gamma_{sc,m} \right) \quad (3)$$

where $n$ is the number of the subcriteria belonging to the specific criterion and *value* is the score assigned to each subcriterion according to evaluation scales set in Table 5.

## 2.3 Resilience

Resilience is modeled by considering those aspects of cultural heritage systems that characterize their coping, adapting, and restoring ability (Fig. 4). The criteria proposed for resilience include:

- CR3.1) Preparedness capacity considers the measures taken to prepare for and reduce the effects of disasters. That is, to predict and—where possible—prevent them, mitigate their impact, and respond to and effectively cope with their consequences. It includes:
  - CR3.1a maintenance: periodic inspection and maintenance of the site is crucial to ensure an optimal performance of the assets in disaster (for example, maintenance plans or schemes);
  - CR3.1b warning: it refers to adequate warning of impending disasters such as sensors to record or

**Table 4** Evaluation scale related to the subcriteria of susceptibility (RQ1)

| Criterion and subcriterion | | Value meaning | Value |
|---|---|---|---|
| CR1.1a | Constructions and materials | Structurally sound constructions made of resistant materials | 0.00 |
| | | Structurally sound constructions made of materials prone to degradation or impact damage | 0.5 |
| | | Structurally weak constructions made of material prone to degradation or impact damage | 1.00 |
| CR1.1b | Use | In continuous use | 0.10 |
| | | Occasional use | 0.40 |
| | | Abandoned | 1.00 |
| CR1.1c | State of conservation | Good | 0.00 |
| | | Fair | 0.18 |
| | | Poor | 0.73 |
| | | Very bad | 1.00 |
| CR1.1d | Previous harming interventions | Yes, previous interventions | 1.00 |
| | | No interventions made | 0.00 |
| CR1.2a | Built elements of decoration | Absence of elements of decoration | 0.00 |
| | | Presence of elements of decoration | 1.00 |
| CR1.2b | Water features | Absence of water features | 0.00 |
| | | Presence of water features | 1.00 |
| CR1.2c | Circulation features | Absence of circulation features | 0.00 |
| | | Presence of circulation features | 1.00 |
| CR1.2d | State of conservation | Good | 0.00 |
| | | Fair | 0.18 |
| | | Poor | 0.73 |
| | | Very bad | 1.00 |
| CR1.3a1 | Species | Presence of species tolerant to local natural and climate threats | 0.00 |
| | | Presence of species not tolerant to local natural and climate threats | 0.30 |
| | | Prevalence of species not tolerant to local natural and climate threats | 1.00 |
| CR1.3a2 | Age | Absence of mature/veteran trees | 0.00 |
| | | Presence of some mature/veteran trees | 0.30 |
| | | Prevalence of mature/veteran trees | 1.00 |
| CR1.3a3 | Slenderness ratio | $h/d < 70$ | 0.00 |
| | | Presence of trees with $h/d > 70$ | 0.30 |
| | | Prevalence of tress with $h/d > 70$ | 1.00 |
| CR1.3b | Grass/shrub cover | Presence of species tolerant to local natural and climate threats | 0.00 |
| | | Presence of species not tolerant to local natural and climate threats | 0.30 |
| | | Prevalence of species not tolerant to local natural and climate threats | 1.00 |
| CR 1.3c | Use | Intensive land use (including urban-sprawl, without natural elements | 0.00 |
| | | Intensive land use with natural elements | 0.30 |
| | | Extensive land use | 1.00 |
| CR1.3d | State of conservation | Good | 0.00 |
| | | Fair | 0.18 |
| | | Poor | 0.73 |
| | | Very bad | 1.00 |
| CR1.4 | Topography | No surrounding slopes | 0.00 |
| | | Stable slopes with inclination less than 15 degrees | 0.15 |
| | | Stable slopes with slope inclination higher than 30 degrees | 0.30 |
| | | Unstable slopes with inclination of 15–30 degrees | 1.00 |
| CR1.5a | Bedrock | Presence of stable bedrock | 0.00 |
| | | Presence of unstable bedrock | 1.00 |
| CR1.5b | Soil | Coarse-grained soil (sand, gravel) | 0.00 |
| | | Fine-grained soil (silt, clay) | 0.30 |
| | | Highly organic soil (peat) | 1.00 |

**Table 4** (continued)

| Criterion and subcriterion | | Value meaning | Value |
|---|---|---|---|
| CR1.5c | Geomorphology | Presence of stable geological formation | 0.00 |
| | | Presence of unstable geological formation | 1.00 |
| CR1.6a | Groundwater | Stable water table | 0.00 |
| | | Water table prone to sudden fluctuations | 1.00 |
| CR1.6b | Surface water | Far from permanent, seasonal, and human-made water course | 0.00 |
| | | Close to permanent, seasonal, and human-made water course | 1.00 |
| CR1.6c | Sea | Far from sea | 0.00 |
| | | Close to sea | 1.00 |

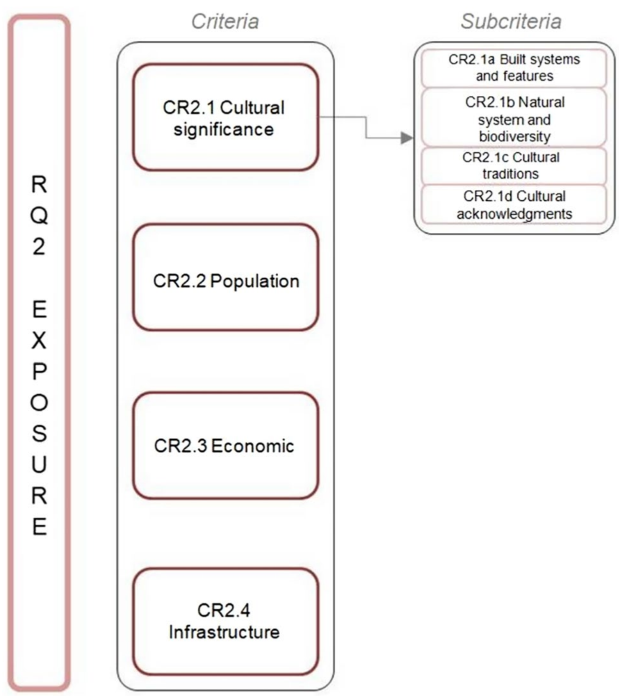


**Fig. 3** Exposure criteria and subcriteria. *RQ* Requirement, *CR* Criterion

predict the onset or likelihood of disaster. Examples include early warning systems for disasters (for example, fire alarms, seismographs), weather alert systems, media or social media alerts by local authorities, and so on;

- CR3.1c knowledge and awareness: gathering, evaluating, and disseminating best practice examples as well as bad ones are also fundamental in order to exploit the full potential of experiences in the perspective of defining an appropriate cultural heritage protection strategy. Awareness, public education, systems, and facilities that provide advice are proven methods for reducing cultural heritage losses. Examples include research funding, training for practitioners, the introduction of technical standards, knowledge-sharing platforms based on digital technologies, regional, national, and transnational programs for knowledge sharing among neighboring areas, dissemination via seminars and lectures or media campaign, on-site disaster simulations and drills, and so on;
- CR3.1d information: understanding and knowing the characteristics of cultural heritage assets and their components represents a fundamental prerequisite for appropriate preparedness. This information enables to establish priorities for the protection of property and for example to guide fire brigades and civil defense officials to handle sensitive areas with care in responding to emergencies. The assessment of cultural heritage values can also help clarify property losses and priority needs for stabilizing and securing the property and its constituent elements during post-disaster processes. Examples include schemes for identifying and marking stock at risk through mapping, condition assessment, and evaluation, the existence of inventories and databases, records, and registers of heritage sites;
- CR3.1e policy and regulation: policies and regulations dictate the capacity of a system to be prepared for the occurrence of disasters. In particular, policies should be tailor-made for risk management of cultural heritage assets. Also, responsibilities among stakeholders must be clearly identified as well as the communication flows in emergencies. Examples include the existence of technical codes for the management of risk (for example, building codes, manuals for parks and gardens, zoning plans, cultural heritage regulations, and so on.

- CR3.2) Coping capacity and adaptive capacity or the ability of a system to adapt to the event without undergoing major transformations and changes. It involves:

**Table 5** Evaluation scale related to the subcriteria of exposure (RQ2)

| Criterion and subcriterion | | Value meaning | Value |
|---|---|---|---|
| CR2.1a | Built systems and features | Absence of built systems and features | 0.00 |
| | | Presence of built systems and features | 1.00 |
| CR2.1b | Natural systems and biodiversity | Absence of natural systems and features | 0.00 |
| | | Presence of natural systems and features with low/medium value for biodiversity | 0.50 |
| | | Presence of natural systems and features with high value for biodiversity | 1.00 |
| CR2.1c | Cultural traditions | Absence of cultural traditions | 0.00 |
| | | Presence of cultural traditions | 1.00 |
| CR2.1d | Cultural acknowledgments (to be adjusted according to the national adopted scale) | None | 0.00 |
| | | Grade IV | 0.27 |
| | | Grade III | 0.61 |
| | | Grade II | 0.86 |
| | | Grade I | 1.00 |
| CR2.2 | Population | No population | 0.00 |
| | | With population but no fragility | 0.30 |
| | | Presence of fragile population | 1.00 |
| CR2.3 | Economic | No economic value | 0.00 |
| | | Livelihoods of local residents | 0.50 |
| | | Presence of stable and ramified system with high economic value | 1.00 |
| CR2.4 | Infrastructure | Absence of relevant infrastructure | 0.00 |
| | | Presence of relevant infrastructure | 1.00 |

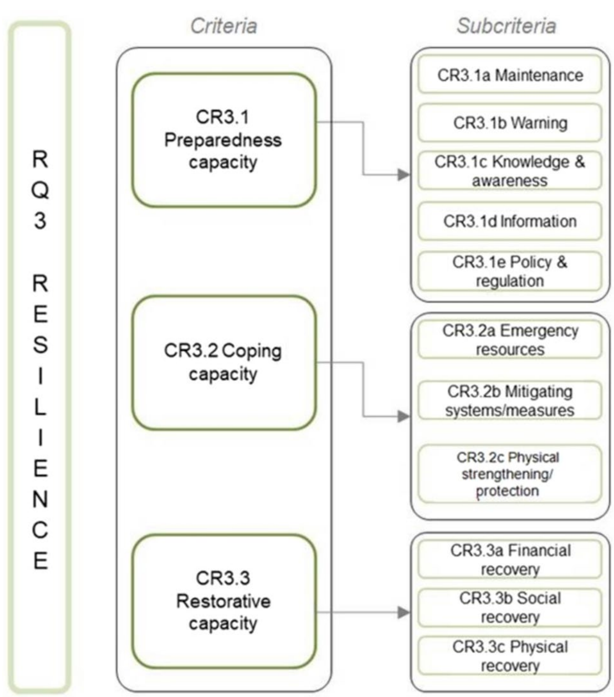


**Fig. 4** Resilience criteria and subcriteria. *RQ* Requirement, *CR* Criterion

- CR3.2a Emergency measures, including emergency management actions such as the activation of the coordinating team and the operative one, rescue teams, emergency management committee, emergency plans, evacuation routes, and so on;
- CR3.2b Mitigating systems/measures, including water damage prevention devices such as drainage ditches, dams, flood gates, spillways, overflow channels;
- CR3.2c Physical strengthening and protection, including defense systems such as barriers, retrofitting of building components, anchoring, strapping, and propping of trees, moveable objects, or built components.

- CR3.3) Restorative capacity, that is, the ability of the system to recover from the initial shock. It includes:

  - CR3.3a financial recovery, including measures for ensuring the recovery of the financial dimension, the existence of specific funds at different administrative levels, and tax relief measures;
  - CR3.3b social recovery, including plans for recovery of livelihoods, health support schemes, emergency accommodation plans, and so on;
  - CR3.3c physical recovery, including reconstruction plans, cleaning and disposal plans, and so on.

**Table 6** Evaluation scale related to the subcriteria of resilience (RQ3)

| Criterion and Subcriterion | | Value Meaning | Value |
|---|---|---|---|
| CR3.1a | Maintenance | No maintenance | 0.00 |
| | | Irregular maintenance | 0.50 |
| | | Regular maintenance | 1.00 |
| CR3.1b | Warning | Absence of early warning systems | 0.00 |
| | | Presence of early warning systems | 1.00 |
| CR3.1c | Knowledge and awareness | Lack of technical knowledge | 0.00 |
| | | No knowledge sharing among stakeholders | 0.50 |
| | | Lack of awareness | 0.80 |
| | | Knowledge and awareness ensured | 1.00 |
| CR3.1d | Information | No information | 0.00 |
| | | Partial, not up-to-date, or incomplete information exist | 0.30 |
| | | Partial or complete information exist but not available | 0.50 |
| | | Complete information is available | 1.00 |
| CR3.1e | Policy and regulation | Lack of regulations for cultural heritage | 0.00 |
| | | Unclear responsibilities | 0.30 |
| | | Ownership status issues | 0.50 |
| | | Regulated cultural heritage protection | 1.00 |
| CR3.2a | Emergency resources | Absence of emergency human and economic resources | 0.00 |
| | | Existence of emergency human and economic resources | 1.00 |
| CR3.2b | Mitigating systems/measures | Absence of mitigating systems | 0.00 |
| | | Existence of mitigating system | 1.00 |
| CR3.2c | Physical strengthening/protection | Absence of physical protection | 0.00 |
| | | Existence of physical protection | 1.00 |
| CR3.3a | Financial recovery | No funds available | 0.00 |
| | | Funds available but not accessible | 0.10 |
| | | Funds available but insufficient | 0.30 |
| | | Funds available and accessible | 1.00 |
| CR3.3b | Social recovery | Absence of social recovery plan | 0.00 |
| | | Existence of social recovery plan | 1.00 |
| CR3.3c | Physical recovery | No risk management plan | 0.00 |
| | | Risk management plan without specific emergency measures | 0.30 |
| | | Risk management plan exists and up to date | 1.00 |

Table 3 presents the selected resilience criteria and subcriteria. Factors $\gamma_{RQ3}$, $\gamma_c$, and $\gamma_{sc}$ refer to the weight assigned to respectively RQ3 (resilience), criteria, and subcriteria, following adjustments of existing knowledge (Hahn et al. 2009; Daly 2014; Gandini et al. 2018; Bosher et al. 2019).

Resilience can be calculated as the weighted sum of all subcriteria factorized by the criterion's coefficient $\gamma_c$, using the formula:

$$RQ3 = \sum_{i=1}^{6} \gamma_{c,i} \left( \sum_{m=1}^{n} (value) \gamma_{sc,m} \right) \tag{4}$$

where $n$ is the number of subcriteria belonging to the specific criterion and *value* is the score assigned to each subcriterion according to evaluation scales set in Table 6.

## 2.4 Evaluation Scales

Indicators or subcriteria can be transformed into comparable and dimensionless units through the use of value functions, resulting in a value between 0 and 1 (Gandini et al. 2018). For each subcriterion, a value function has been created, to evaluate the different alternatives compiled in evaluation scales. In cases where the value function was not available in the literature, it was defined by an expert group. Tables 4, 5, and 6 outline the evaluation scales related to the susceptibility, exposure, and resilience subcriteria. Each subcriterion is assigned alternatives (ranking) with a corresponding value, which is used in Eqs. 2, 3, and 4 for the assessment of requirements RQ1, RQ2, and RQ3.

**Table 7** Description of the different testing sites, specifying the geographical location and their peculiar heritage categories and relevance, highlighting elements under threat and main hazards impacting the site

| Place | Assessed site | CNH | Cultural relevance | Elements under threat | Impacting hazards |
|---|---|---|---|---|---|
| Troja Hamlet<br>Troja-Praha<br>(CZ) | *Troja Château* | H<br>HPG<br>M | Historic landscape<br>Historic buildings<br>Architectural heritage | Landscape<br>Building materials<br>Flora and fauna | Flood<br>Windstorm<br>Fire |
| Franconian Switzerland Bavaria (DE) | *Cherry fields*<br>*Walberia* | CL<br>H | Mountain and hill CNH, high density of castles and ruins | Landscape<br>Building materials<br>Fruit growing<br>Rural settlements | Flash flood<br>Storm<br>Drought<br>Heat |
| Kolici<br>Split-Dalmatia (HR) | *Kolici* | H | Mountain hamlets with preserved authentic stone construction methods, typical for Dalmatian architecture | Stone constructions (building, walls, elements) | Landslide<br>Drought<br>Fire |
| Parco Villa Ghigi<br>Bologna, (IT) | *Parco Villa Ghigi* | CL<br>HPG | Protected natural and semirural hill area including a seventeenth-century manor and centuries-old trees including monumental specimen protected at the national level | Landscape<br>Flora and fauna<br>Building materials | Heavy rain<br>Flash flood<br>Landslide<br>Windstorm |
| Wachau Valley<br>Krems, Stein, Melk (AT) | *Melk Abbey landscape*<br>*Dürnstein*<br>*Krems Stejn* | CL<br>H<br>R | Multitude of CNH: historic city centers, monasteries, ruins, hamlets, terraced vineyards, apricot trees | Landscape<br>Dry stone walls<br>Building materials<br>Fruit growing | Heavy rain<br>River flood<br>Flash flood<br>Landslide<br>Fire |
| Lake Balaton (HU) | *Zichy Mansion* | CL<br>HB<br>HPG<br>M | Significant historical, cultural, and ecological values: 81 settlements involved in geoparks, Natura 2000 sites, 116 locally protected nature areas, 2,935 historic buildings, historic gardens | Landscape<br>Flora and fauna<br>Building materials | Lake flood<br>Flash flood<br>Windstorm<br>Erosion<br>Landslide<br>Fire due to drought |
| Vipava Valley (SI) | *Lanthieri Manor*<br>*House Miren 114 & 137*<br>*Linden tree line*<br>*Rence Church*<br>*Rence School* | CL<br>HB<br>M<br>R | Built cultural heritage: many monuments with a status of national or local importance | Landscape<br>Building materials | Heavy rain<br>River flood<br>Landslide<br>Windstorm |

*CL* cultural landscape, *CNH* cultural and natural heritage, *H* hamlets, *HB* historic buildings, *HPG* historic parks and gardens, *M* mansions, *R* ruins

Following the vulnerability definition provided in Sect. 2 and the aggregation method presented in Eq. 1, vulnerability is computed as follows:

$$V = \left(\gamma_{RQ1}RQ1 + \gamma_{RQ2}RQ2\right) - \gamma_{RQ3}RQ3 \quad (5)$$

The computed values allow vulnerability ranking for different cultural heritage assets. The application of this methodology in the field of cultural heritage protection allows drafting vulnerability maps that, in turn, could support adequate decision making in disaster situations.

## 3 Case Study Applications

The proposed vulnerability assessment methodology has been applied to 15 case studies located in seven European countries (Italy, Austria, Hungary, Slovenia, Czechia, Croatia, and Germany). These represent a wide range of different cultural and natural heritage categories, such as cultural landscape, historic garden and park, archaeological site, small ruined village, and historic building, in different geographical and environmental context (urban and remote sites in mountainous, hilly, and coastal areas). Key to the selection of the most appropriate sites for the vulnerability assessments is the exposure of the sites to hazards influenced by climate change: heavy rains, flash floods, flood events in large basins, windstorms, and fires due to drought periods (Table 7 and Fig. 5). Detailed descriptions of the case studies are available on the website of the STRENCH Project.[2]

[2] https://programme2014-20.interreg-central.eu/Content.Node/STRENCH.html


**Fig. 5** Representative pictures (©STRENCH Project) of the case study sites evaluated: Five places for cultural landscape; four places for hamlets; one place for historic buildings/complex; three for historic parks and gardens; three for mansions; and two places for ruins. *CNH* cultural and natural heritage

### 3.1 Ranking of Susceptibility, Exposure, and Resilience

This section summarizes the results of the final evaluation of susceptibility, exposure, and resilience performed in each case study. The assessment was carried out with the support of the local stakeholders, following the methodology described in Sect. 2. Professionals, managers of cultural and natural heritage resources, and members of local public authorities have been involved during the whole process to define the most appropriate indicators and assign the correct weights, as reported in Sect. 2.4 (Tables 1, 2, and 3). Following an iterative process, feedback obtained after the first consultation had a pivotal role in the adaptation and adjustment of the methodology and in the correct assignment of the evaluation to the subcriteria. The final result was a fine-tuned procedure for specific cultural and natural heritage categories in different environmental contexts affected by diverse hazards (Table 7 and Fig. 5).

For Table 7's case studies, the value assigned to each subcriterion is reported for the three requirements of susceptibility (Table 8), exposure (Table 9), and resilience (Table 10). The values assigned to each subcriterion, ranging from 0.00 to 1.00, are also represented as a proportional color bar in red in Tables 8 and 9, to highlight that increasing relative values of susceptibility and exposure account for an increase of vulnerability, and in green in Table 10 to emphasize that increasing relative values of resilience imply a decrease of vulnerability.

### 3.2 Ranking of Vulnerability for Each Case Study

Vulnerability (V), computed using Eq. 5, ranges between 0.00 and 1.00 and can be ranked in five different categories (Balica et al. 2012), as follows:

Very low:$0.0 \leq V < 0.2$ slightly susceptible assets with high level of protection
Low:$0.2 \leq V < 0.4$ moderately susceptible assets with moderate level of protection
Moderate:$0.4 \leq V < 0.6$ highly susceptible assets with moderate level of protection
High:$0.6 \leq V < 0.8$ very highly susceptible assets with low level of protection
Very high:$0.8 \leq V < 1.0$ very highly susceptible assets with no protection

Table 11 reports the values of vulnerability obtained for each site, alongside the values of susceptibility (RQ1), exposure (RQ2), and resilience (RQ3) from Tables 8, 9, and 10.

**Table 8** The assigned value for each subcriterion of the requirement susceptibility (RQ1) in vulnerability assessment of specific cultural heritage categories considered for the 15 case studies

| | Troja Hamlet (CZ) | Franconian Switzerland (DE) | | Kolici (HR) | Parco Villa Ghigi (IT) | Wachau Valley (AT) | | | Lake Balaton (HU) | Vipava Valley (SI) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Subcriteria** | *Troja Château* | *Cherry fields* | *Walberia* | *Kolici* | *Parco Villa Ghigi* | *Melk Abbey landscape* | *Dürnstein* | *Krems Stejn* | *Zichy Mansion* | *Lanthieri Manor* | *House Miren 114* | *House Miren 137* | *Linden tree line* | *Vipava Rence Church* | *Rence School* |
| CR1.1a | 0.50 | 0.00 | 0.00 | 0.50 | 0.00 | 0.00 | 0.00 | 0.00 | 0.50 | 0.00 | 0.00 | 0.00 | 0.50 | 0.00 | 1.00 |
| CR1.1b | 0.10 | 0.00 | 0.40 | 1.00 | 0.00 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| CR1.1c | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.18 | 0.18 | 0.00 | 0.73 | 0.00 | 0.00 | 0.00 | 0.00 |
| CR1.1d | 1.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1 | 1.00 | 0.00 |
| CR1.2a | 1.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 1.00 | 0.00 |
| CR1.2b | 1.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CR1.2c | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CR1.2d | 0.18 | 0.00 | 0.18 | 1.00 | 0.18 | 0.00 | 0.00 | 0.18 | 0.18 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CR1.3a1 | 0.00 | 1.00 | 0.00 | 1.00 | 0.30 | 0.00 | 0.30 | 0.00 | 0.30 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CR1.3a2 | 0.00 | 0.30 | 0.00 | 1.00 | 1.00 | 0.30 | 0.30 | 0.30 | 0.30 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CR1.3a3 | 0.00 | 0.00 | 0.00 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CR1.3b | 0.30 | 0.30 | 0.00 | 0.30 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CR 1.3c | 0.30 | 0.30 | 1.00 | 1.00 | 1.00 | 0.30 | 0.30 | 0.30 | 1.00 | 0.00 | 0.00 | 0.00 | 0.30 | 0.00 | 0.00 |
| CR1.3d | 0.00 | 0.00 | 0.18 | 1.00 | 0.18 | 0.00 | 0.00 | 0.18 | 0.18 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CR1.4 | 0.15 | 0.15 | 0.15 | 0.30 | 1.00 | 0.30 | 0.30 | 0.15 | 0.15 | 0.30 | 0.00 | 0.15 | 0.00 | 0.00 | 0.00 |
| CR1.5a | 0.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CR1.5b | 0.00 | 0.30 | 0.30 | 0.00 | 0.30 | 0.30 | 0.30 | 0.00 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.00 |
| CR1.5c | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CR1.6a | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 | 0.80 | 1.00 | 1.00 |
| CR1.6b | 1.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 |
| CR1.6c | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **RQ1** | **0.33** | **0.16** | **0.25** | **0.54** | **0.48** | **0.22** | **0.23** | **0.22** | **0.33** | **0.21** | **0.22** | **0.14** | **0.20** | **0.16** | **0.20** |

The value ranging from 0.00 to 1.00 is also represented as a proportional color bar in red in order to emphasize that increasing relative values of susceptibility account for an increase of vulnerability

*RQ* requirement, *CR* criterion

**Table 9** The assigned value for each subcriterion of the requirement exposure (RQ2) in the vulnerability assessment of specific cultural heritage categories considered for the 15 case studies

| | Troja Hamlet (CZ) | Franconian Switzerland (DE) | | Kolici (HR) | Parco Villa Ghigi (IT) | Wachau Valley (AT) | | | Lake Balaton (HU) | Vipava Valley (SI) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Subcriteria** | *Troja Château* | *Cherry fields* | *Walberia* | *Kolici* | *Parco Villa Ghigi* | *Melk Abbey landscape* | *Dürnstein* | *Krems Stejn* | *Zichy Mansion* | *Lanthieri Manor* | *House Miren 114* | *House Miren 137* | *Linden tree line* | *Vipava Rence Church* | *Rence School* |
| CR2.1a | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 |
| CR2.1b | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 0.00 | 0.50 | 0.00 | 1.00 | 0.00 | 0.00 |
| CR2.1c | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 |
| CR2.1d | 0.86 | 0.86 | 1.00 | 0.00 | 0.86 | 1.00 | 0.86 | 0.61 | 0.61 | 1.00 | 0.61 | 0.86 | 1.00 | 0.86 | 0.61 |
| CR2.2 | 0.30 | 0.30 | 0.00 | 0.00 | 1.00 | 0.30 | 1.00 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 1.00 | 0.30 | 0.30 |
| CR2.3 | 0.50 | 0.50 | 0.50 | 0.00 | 0.50 | 1.00 | 0.50 | 0.50 | 0.50 | 0.50 | 0.00 | 0.00 | 0.30 | 0.00 | 0.50 |
| CR2.4 | 1.00 | 0.00 | 0.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 |
| **RQ2** | **0.69** | **0.44** | **0.50** | **0.48** | **0.68** | **0.86** | **0.83** | **0.71** | **0.66** | **0.66** | **0.56** | **0.54** | **0.48** | **0.54** | **0.68** |

The value ranging from 0.00 to 1.00 is also represented as a proportional color bar in red in order to emphasize that increasing relative values of exposure account for an increase of vulnerability

*RQ* Requirement, *CR* Criterion

In 13 out of 15 of the sites considered, susceptibility (RQ1) ranges from very low to low, with a moderate level recorded only for two cases representing diverse cultural heritage categories: 0.54 for Kolici (hamlet) and 0.48 for Parco Villa Ghigi (historic park and garden). Subcriteria related to the built and natural environment (Fig. 2, Sect. 2.1) play a driving role in determining the higher values of susceptibility. In particular, these subcriteria include the use and state of conservation of the heritage site and surrounding environment, the presence/absence of water circulation features at the site, and the hydrogeological and geomorphological conditions of the area in which the sites are located. For both sites a key subcriterion is also given by the presence of mature/veteran trees (Criteria CR1.3 "Vegetation"). Generally, susceptibility for the majority of the investigated sites, particularly built heritage, is highly influenced by the hydrogeological conditions of the area (Subcriteria CR1.6a "Groundwater" and CR1.6b "Surface water"). Previous harming interventions influence the value of susceptibility of a significant number of analyzed sites (Troja Château, Walberia, Zichy Mansion, House Miren, Rence Church), as well as the added architectural

**Table 10** The assigned value for each subcriterion of the requirement resilience (RQ3) in the vulnerability assessment of specific cultural heritage categories considered for the 15 case studies

| | Troja Hamlet (CZ) | Franconian Switzerland (DE) | | Kolici (HR) | Parco Villa Ghigi (IT) | Wachau Valley (AT) | | | Lake Balaton (HU) | Vipava Valley (SI) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Subcriteria** | *Troja Château* | *Cherry fields* | *Walberia* | *Kolici* | *Parco Villa Ghigi* | *Melk Abbey landscape* | *Dürnstein* | *Krems Stejn* | *Zichy Mansion* | *Lanthieri Manor* | *House Miren 114* | *House Miren 137* | *Linden tree line* | *Vipava Rence Church* | *Rence School* |
| CR3.1a | 0.50 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 |
| CR3.1b | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| CR3.1c | 1.00 | 0.80 | 0.80 | 0.80 | 1.00 | 1.00 | 1.00 | 1.00 | 0.80 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| CR3.1d | 0.50 | 0.50 | 0.50 | 0.00 | 0.30 | 1.00 | 1.00 | 1.00 | 0.30 | 0.50 | 0.50 | 1.00 | 1.00 | 1.00 | 0.50 |
| CR3.1e | 1.00 | 0.50 | 1.00 | 0.30 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| CR3.2a | 1.00 | 0.00 | 1.00 | 0.00 | 0.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| CR3.2b | 1.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| CR3.2c | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 1.00 | 0.00 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | - | 1.00 | 1.00 |
| CR3.3a | 0.30 | 0.30 | 0.10 | 0.00 | 0.30 | 1.00 | 1.00 | 0.30 | 0.30 | 0.30 | 0.00 | 0.30 | 0.30 | 1.00 | 1.00 |
| CR3.3b | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.30 |
| CR3.3c | 1.00 | 0.00 | 0.30 | 1.00 | 0.30 | 1.00 | 0.00 | 1.00 | 0.30 | 0.30 | 0.00 | 1.00 | 0.30 | 0.30 | 0.00 |
| **RQ3** | **0.76** | **0.43** | **0.66** | **0.20** | **0.63** | **0.83** | **0.48** | **0.87** | **0.57** | **0.77** | **0.44** | **0.87** | **0.73** | **0.86** | **0.81** |

The value ranging from 0.00 to 1.00 is also represented as a proportional color bar in green in order to emphasize that increasing relative values of resilience implies a decrease of vulnerability

*RQ* Requirement, *CR* Criterion

**Table 11** Susceptibility (RQ1), exposure (RQ2), resilience (RQ3), and vulnerability assessed for each site

| Place | Assessed Site | CNH class | Assessment Results | | | |
|---|---|---|---|---|---|---|
| | | | RQ1 | RQ2 | RQ3 | Vulnerability |
| Troja Hamlet (CZ) | *Troja Château* | HPG, M, H | 0.33 | 0.69 | 0.76 | 0.21 |
| Franconian Switzerland (DE) | *Cherry fields* | CL | 0.15 | 0.44 | 0.43 | 0.11 |
| | *Walberia* | CL, H | 0.25 | 0.50 | 0.66 | 0.13 |
| Kolici (HR) | *Kolici* | H | 0.54 | 0.48 | 0.20 | 0.46 |
| Parco Villa Ghigi (IT) | *Parco Villa Ghigi* | CL, HPG | 0.48 | 0.68 | 0.63 | 0.36 |
| Wachau Valley (AT) | *Melk Abbey landscape* | CL, H, R | 0.22 | 0.86 | 0.83 | 0.16 |
| | *Dürnstein* | CL, H, R | 0.23 | 0.83 | 0.48 | 0.28 |
| | *Krems Stejn* | CL, H | 0.23 | 0.71 | 0.87 | 0.11 |
| Lake Balaton (UR) | *Zichy Mansion* | CL, HPG, M | 0.33 | 0.66 | 0.57 | 0.26 |
| Vipava Valley (SI) | *Lanthieri Manor* | M | 0.21 | 0.66 | 0.77 | 0.11 |
| | *House Miren 114* | HB | 0.22 | 0.56 | 0.44 | 0.19 |
| | *House Miren 137* | HB | 0.14 | 0.54 | 0.87 | 0.00 |
| | *Linden tree line* | CL, R | 0.20 | 0.48 | 0.73 | 0.06 |
| | *Rence Church* | HB | 0.16 | 0.54 | 0.86 | 0.02 |
| | *Rence School* | HB | 0.20 | 0.66 | 0.81 | 0.10 |

*CNH* cultural and natural heritage, *CL* cultural landscape, *H* hamlets, *HB* historic buildings, *HPG* historic parks and gardens, *M* mansion, *R* ruins

value given by the presence of decorative elements at all sites of the Wachau Valley, in addition to the sites located in Czech Republic, Italy, Hungary, and Slovenia.

Exposure (RQ2) varies from moderate to very high, with the highest levels for the heritage sites located in the Wachau Valley. The subcriteria influencing the cultural significance (Criterion CR2.1) have a key influence in determining the higher encountered values, not only for the sites of the Wachau Valley, but also in general for all the other sites. The presence of relevant infrastructure (CR2.4) at almost all sites has also been recognized as driving the final value of this requirement. The presence of population, as another significant criterion (CR2.2), should be considered, particularly for the Italian, Slovenian, and Austrian sites.

Resilience (RQ3) generally varies from moderate to very high, with only one case study presenting a low value (Kolici). The ruined hamlet located in Croatia lacks in preparedness capacity (Criterion CR3.1), particularly when referring to maintenance intervention, early warning systems, information, and knowledge about the characteristics of the cultural heritage assets. The site is characterized also by presenting a low value concerning subcriterion CR3.1e related to policy and regulation. Significant gaps are also recognized for the other two criteria: coping capacity (CR3.2) and restorative capacity

(CR3.3). Concerning the latter, an existing and updated risk management plan (CR3.3.c) positively influences the resilience of the site. The highest values of resilience are found at the sites located in the Wachau and Vipava valleys.

In summary, in 93% of the cases, susceptibility is lower than 0.5, indicating light to moderate predisposition to damage. Similarly, 73% of the sites record an exposure higher than 0.5, evidencing the cultural relevance and intrinsic values of the selected case studies. Finally, 73% of the sites score a resilience higher than 0.5, exposing the high level of protection implemented at the sites with considerable influence in reducing vulnerability.

Concerning the final vulnerability evaluation, 70% of the selected cases scored $V < 0.2$ (very low), 25% $0.2 \leq V < 0.4$ (low), and only 5% attained a vulnerability value $0.4 \leq V < 0.6$ (moderate). No tested site presents a high or very high category of vulnerability ($V \geq 0.6$). This shows that no significant damage is expected from hazards. Nevertheless, due to the considerable heritage value of the assets analyzed, deeper insights into the actual conditions in situ are needed with a quantitative investigation of resilience and susceptibility factors.

The testing on 15 case studies represents diverse cultural and natural heritage categories located in diverse environmental and climate contexts in Central Europe. Characterized by different approaches in managing cultural heritage at risk, it allows the achievement of significant steps in the validation of the proposed methodology. A key phase was the iterative consultation with local stakeholders for the final identification of the criteria and subcriteria to adjust the given values. Application to further sites in other contexts would contribute to strengthening the reliability of the methodological approach.

For the case studies investigated, the meaning of vulnerabilities below 0.5 is presented in the discussion of the results. Being culturally significant in their countries, the selected sites mostly present a high level of protection and maintenance, that is, resilience, reducing vulnerability. Some also present high susceptibility, that is, intrinsic predisposition to damage. The in-depth analysis of the criteria and subcriteria crucial for the final value of each requirement permits tracking down the weaknesses and strengths of the site from the environmental (natural and built), cultural, social, and managerial perspectives. Therefore, it permits the identification of the priorities for safeguarding the site. The development of a standardized methodology of vulnerability assessment going beyond merely qualitative evaluations is needed to support heritage managers and decision makers to undertake suitable actions of preparedness and preventive conservation.

## 4 Concluding Remarks and Future Directions

The proposed methodology represents a valid tool for targeted users, including non-technical ones, for the sake of vulnerability assessment of cultural and natural heritage in conditions of risk linked to hydrometeorological extremes. The underlying conceptual framework, based on MCDA and on widely accepted representations of vulnerability, ensures reliable modeling of the domain with considerable adaptability and transferability capacities. Its novelty is represented by the possible applicability to diverse cultural heritage potentially at risk from various hazards linked to climate change.

The validation of the methodology, carried out through the investigation of vulnerability at selected case study sites, exposes the main advantages of the evaluation tool. First, the model is easy to use and intuitive, despite the high complexity of the domain involved. Second, the ease-to-use enables better accessibility, optimizing awareness raising and the dissemination of results. Finally, the methodology allows gathering immediate vulnerability evaluation data, even with limited or remote access to the site, thanks to the low-resource demanding calculation process involved. The tool successfully helps to flag critical situations, that is, those conditions under which cultural heritage assets are more prone to experience damage or loss. It also provides an indication of which specific factors of susceptibility, exposure, and resilience should be addressed. From this perspective, the vulnerability methodology constitutes an opportunity for managers and decision makers to optimize resource allocation and prioritize interventions for the protection of cultural and natural heritage.

Nevertheless, limitations should be considered. The assessment is mostly qualitative. For obtaining a more accurate vulnerability evaluation, a thorough assessment using quantitative indicators would be needed. Due to the heterogeneity of cultural and natural heritage typologies considered, the diverse scale of analysis is not distinguished by the model. Knowing the strong scale dependency of vulnerability, it is recommended that its effects should be factored in separately by the evaluator, especially when comparing results from different assets. In addition, the partial use of the model is not supported. The assessment of only some of the criteria or subcriteria, in fact, would result in mis-estimating vulnerability. Similarly, the model does not capture cases of lacking, incomplete, or unknown data. Finally, there exist synergic effects due to the co-existence of particular susceptibility, exposure, and resilience conditions that may result in a considerably increased vulnerability of the asset under investigation. This should be taken into consideration during the evaluation.

The proposed model results from iterations, adapting it to fulfill requirements from the selected case studies. As a result, its branches differ in depth with some being particularly detailed (for example, vegetation) and others being strongly simplified (for example, construction and material). Nevertheless, a more articulated structure of the criteria can be easily integrated for future work.

Future work should primarily consider extending the testing phase at the local level by actively engaging stakeholders with a deepened knowledge of the territories under evaluation and their challenges, the value and significance of the heritage assets to be protected, and existing risk management systems (strategies and plan). This would allow further framework validation and adjustments of the requirement tree, weights, and evaluation scales. It would also permit overcoming or controlling most of the limitations outlined above. The gained experience highlights the need to integrate precise indicators, which could allow quantitative vulnerability assessment. Moreover, enlarging the stakeholders defining the conceptual framework and its variables will benefit the optimization and soundness of the methodology. Implementing the methodology in existing tools for risk management would contribute to improving its robustness and effectiveness as well as its dissemination and outreach.

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