International Journal of Disaster Risk Science (2023) 14:26–40
https://doi.org/10.1007/s13753-023-00463-4

www.ijdrs.com
www.springer.com/13753

ARTICLE

A Vulnerability Assessment Framework for Cultural Heritage Sites: The Case of the Roman Ruins of Tróia

Marvin Ravan[1] · Maria João Revez[2] · Inês Vaz Pinto[3] · Patrícia Brum[3] · Joern Birkmann[1]

Accepted: 21 January 2023 / Published online: 7 February 2023

Abstract
This article contributes to developing an indicator-based vulnerability assessment framework for cultural heritage sites. It provides a vulnerability index for heritage sites potentially exposed to multiple hazards, including sudden-onset and slow-onset hazards, while considering climate change influences. Through determining particular criteria and indicators, the Cultural Heritage Vulnerability Index incorporates structural and non-structural factors of the heritage site and its local and national settings. The assessment procedure was applied to the case of the Roman Ruins of Tróia in Portugal. The findings highlight those areas of sensitivity (e.g., the existing deterioration patterns and types of foundation) and coping and adaptive capacities (e.g., institutional setting and response plan) that significantly contribute to the level of vulnerability and risk. The results of vulnerability assessment will further enable determining priorities and developing risk mitigation and preparedness measures, in particular reducing structural sensitivity and promoting coping capacities.

Keywords Climate change · Coping capacity · Cultural heritage · Risk assessment · Roman Ruins of Tróia · Vulnerability assessment

1 Introduction

Cultural heritage properties are exposed to the adverse effects of natural hazards, with consequences ranging from gradual decay and deterioration to outright catastrophic losses. The increased frequency and intensity of extreme weather events as a result of climate change has worsened the situation, calling for integrated methodologies and processes for risk assessment and management applicable to heritage conservation. Risk assessment has increasingly become the methodology of choice in implementing planned maintenance and preventive conservation programs since it facilitates the integration of all available knowledge and its operational streamlining. Risk assessment of cultural heritage sites needs to be able to integrate information on both sudden- and slow-onset events, for example when it comes to structural vulnerability, to adequately provide priorities for future risk treatment strategies. Admittedly, the vulnerability of a heritage site is strongly related to its structural and material features, which dictate how the site will respond to the different threats facing it. To account for these variable responses, a vulnerability analysis must consider not only the materials used to build the object and their respective resistance to different stressors, but also how these materials will work as a whole, that is, how they are structured, and how this structure will withstand the impacts to which it is exposed. What is more, the conservation condition of the object, at the material and structural level, will be a determinant in estimating the probable impacts of a hazardous event (Daly 2014; Ortiz and Ortiz 2016). Given the eminently technical nature of these analyses, the involvement of experts with knowledge and working experience on cultural heritage is paramount (Tolles et al. 2002).

Vulnerability goes beyond the mere structural performance of the heritage buildings (or objects), encompassing the capacity of the management system and institutional settings to cope with the consequences of natural hazards and adapt to the gradual changes of the climate. Heritage is a cross-sectoral area that has strong links with various departments including cultural heritage authorities and other

---

✉ Marvin Ravan
marvin.ravan@ireus.uni-stuttgart.de

[1] Institute of Spatial and Regional Planning (IREUS), University of Stuttgart, 70569 Stuttgart, Germany

[2] Nova Conservação, S.A, 1200-872 Lisbon, Portugal

[3] Troia Resort, 7570-789 Carvalhal, GDL, Portugal

organizations, urban planning, environmental planning, civil protection, and so on. Risk-preparedness for cultural heritage is dependent upon prevailing risk-preparedness policies and practices established at the national, regional, and local levels. While the coping and adaptive capacities of cultural heritage to disaster risks are contingent upon a multitude of factors, the role of governance context, including legal, policy, and institutional frameworks, is highly instrumental in facilitating a holistic management approach to resilient heritage.

Existing vulnerability assessment methods for historical sites mainly concentrate on structural factors and the modeling of potential impacts (D'Ayala et al. 2006; Lagomarsino 2008; Ortiz and Ortiz 2016; Romao et al. 2016; Sevieri et al. 2020), while only a few have addressed non-structural determinants related to coping capacity and institutional factors (Phillips 2015; Sesana et al. 2018). Recognizing this challenge, integrated approaches are needed to incorporate the structural (structural and material performance) and non-structural (coping and adaptive capacities) factors into the vulnerability assessment of cultural heritage.

This study aims to contribute to an integrated framework of vulnerability assessment for cultural heritage sites exposed to multiple hazards, exemplified for the Roman Ruins of Tróia, Portugal. It provides a vulnerability index for heritage sites potentially exposed to multiple natural hazards, including sudden-onset and slow-onset hazards, while considering climate change influences. Through determining particular criteria and indicators, the Cultural Heritage Vulnerability Index (CHVI) incorporates structural and non-structural factors into the assessment procedure. It finally demonstrates how the output contributes to decision making for determining priorities and developing risk mitigation and preparedness measures, in particular reducing structural sensitivity and promoting coping capacities. The proposed method mainly targets cultural heritage sites, particularly large-scale sites, to provide a vulnerability assessment of the different areas of a site to multiple hazards and facilitate risk management at site level. This provides an overall vulnerability assessment; when it comes to a building exposed to a specific hazard, for example, seismic performance of the structures, further structural analysis is needed.

2 Conceptual Framework

The interrelations between disaster risk and vulnerability associated with natural hazards or climate change have been discussed widely among a range of scholars and disciplines (Cardona et al. 2012), and it is well established that vulnerability is a key component of risk for determining risk reduction and climate change adaptation strategies. The multi-dimensional nature of vulnerability has led to different definitions, approaches, and methods in its corresponding disciplines. Taking into account the existing variety of approaches to assessing vulnerability (Bogardi and Birkmann 2004; Füssel and Klein 2006; Birkmann 2013; IPCC 2014; Jurgilevich et al. 2021), as well as considering the evolving understanding of the concept and its dynamic nature, it is important to illustrate the established definitions of the term in the context of disaster risks and climate change.

2.1 Vulnerability

Vulnerability may be construed as "the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to hazard, either a perturbation or stress/stressor" (Turner et al. 2003, p. 8074). This physical perspective of vulnerability is mostly focused on impact or damage analysis and will assess the properties of a system in terms of their potential to reduce or amplify the hazard impacts (Brooks 2003). In turn, a social definition of vulnerability considers it to be "an inherent property of a system arising from its internal characteristics" (Brooks 2003, p. 4), which may encompass "the characteristics of a person or group and their situation that influences their capacity to anticipate, cope with, resist, and recover from the adverse effects of physical events" (Wisner et al. 2004, p. 11). In this perspective, vulnerability is viewed as a state, that is, inherent to the system irrespectively of the (external) hazards affecting it. In the context of climate change adaptation research, vulnerability is defined as "the propensity or predisposition to be adversely affected" (IPCC 2018, p. 560). In the Intergovernmental Panel on Climate Change (IPCC) agenda, vulnerability may incorporate a variety of concepts and components, notably including "sensitivity" or "susceptibility to harm" and "lack of capacity to cope and adapt" (IPCC 2014).

Despite various frameworks developed for defining and assessing vulnerability, it is interesting to note that at least some common causal factors of vulnerability have been identified, in both the disaster risk management and climate change adaptation communities (Birkmann et al. 2013; Cardona 2013; IPCC 2014; Schneiderbauer et al. 2017; Kelman 2018). The first factor is susceptibility or sensitivity, which refers to the physical predisposition of the elements exposed to hazards; and the second factor is lack of resilience or lack of coping and adaptive capacities due to limitations in access to and/or in mobilization of resources to respond and recover from the adverse consequences of hazards.

In the current framework proposal, susceptibility or sensitivity will be taken to mean "an inherent property of a [system], distinguished from its capacity of response" or, in other words, "an attribute of the system, existing prior to the perturbation, and separate from exposure" (Gallopín

2006, p. 296). Coping capacity is "the combination of all the strengths, attributes and resources available within an organisation, community or society to manage and reduce disaster risks and strengthen resilience" (UNISDR 2015, p. 9). Adaptive capacity, is "the ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences" (IPCC 2018). While the focus of coping is on immediate reaction, adaptive capacity implies a long-term strategy that provides community with the possibility of change and transform needed to deal with potential adverse effects of climate change threats (Birkmann et al. 2013).

2.2 Vulnerability in Cultural Heritage Contexts

Different physical factors have been determined to influence the potential for damage in historic buildings, such as structural and foundation system, architectural features, reinforcement measures, condition of building materials, and physical and chemical characteristics (Tolles et al. 2002; D'Ayala et al. 2006; Lagomarsino 2008; Ortiz and Ortiz 2016). D'Ayala et al. (2006) proposed a model—Multi-Hazard Assessment of Vulnerability (applied to historic buildings)—whereby vulnerability to four sudden-onset hazards (earthquakes, windstorms, floods, and lightening) may originate in the "physical attributes and structural behavior" or in the "cultural attributes and significance potential loss" of the building. Quattrone (2016) emphasizes that "the vulnerability of an asset is concretely manifested in [its] state of conservation: it is therefore, a measurable dimension through the various aspects of degradation" (2016, p. 160). This measurement resorts to conservation condition indicators relating weathering phenomena (e.g., "structural damage" or "humidity") with building components (e.g., "foundations" or "vertical connections"), to be (semi-quantitatively) rated by heritage and/or site experts.

Ortiz and Ortiz (2016) and Rodríguez-Rosales et al. (2021) considered the vulnerability of a monument to correspond to its "current conservation condition" and proposed a Vulnerability Index where the seriousness and frequency of the weathering forms present in the building—as defined by Fitzner (2007) and ICOMOS-ISCS (2008)—are (semi-quantitatively) computed to estimate its resistance to the impacts of pre-selected sudden- and slow-onset hazards that may commonly affect the study area, categorized using the Italian Risk Map classification (Baldi et al. 1995). Appiotti et al. (2020) divided the vulnerability of single heritage buildings into three analytical components: structural, related to static properties; functional, related to building use; and formal, related to valuable building component. Their corresponding vulnerability is assessed semi-quantitatively via expert consultation and varies according to the specific hazard under analysis.

Seismic risks are arguably the field where more vulnerability studies have been performed for cultural heritage sites using the mathematical modeling of structural behavior. Berto et al. (2017) and Cantagallo et al. (2020) described recent application examples, using information obtained from extensive surveys of the historic environment following the "knowledge path" defined by the Italian Civil Protection Services and Ministry of Cultural Heritage: historical analysis, geometric measurements, construction materials, and state of deterioration. Other approaches, for example, Lagomarsino (2006) and Podestà and Romano (2014), proposed vulnerability curves for frequently found heritage typologies (church, monastery/convent, mosque, tower, and so on). A large number of studies have been also dedicated to the vulnerability analysis and modeling of cultural heritage to other types of hazards such as flooding (Garrote et al. 2020; Figueiredo et al. 2021) and fires (Salazar et al. 2021).

The field of cultural heritage has only recently gained attention within the coping and adaptive capacity discourse. Coping and adaptive capacities heavily rely on the heritage management system and institutional settings. Through reviewing the existing literature, relevant criteria influencing coping capacities at site and regional levels can be determined. Examples of such factors are adequacy of structural reinforcement, risk awareness, emergency response plans, emergency response drills and simulations, documentation, storage and salvage, human and financial resources, availability of experienced professionals, and security and fire alarm systems (Stovel 1998; FEMA 2005; Lagomarsino 2008; UNESCO et al. 2010; Phillips 2015; Michalski and Pedersoli 2016). However, the integration of coping and adaptive capacity indicators into the methodology of vulnerability and risk assessment needs further development to adequately inform risk reduction strategies.

3 Methodology: Vulnerability Assessment Framework

In general, three major standardization schemes can be distinguished for vulnerability assessment: vulnerability matrix, vulnerability index, and vulnerability curves (Papathoma-Köhle et al. 2017; Zschau 2017). As provided in Zschau 2017, a vulnerability matrix is a table that relates expected levels of damage to certain hazard intensities, where the results can be represented either in qualitative or quantitative terms. The method could be subjective (Papathoma-Köhle et al. 2017). In comparison, a quantitative method for vulnerability assessment is provided by vulnerability curves. Tarbotton et al. (2015, p. 121) defined empirical vulnerability functions (or curves) as "a continuous curve associating the intensity of the hazard (X-axis) to the damage response of a building (Y-axis)"; it considers only structural damages. An example of the development of vulnerability curves specific to cultural heritage was done by Figueiredo et al. (2021).

This study adapted the vulnerability index method to assess the vulnerability of cultural heritage. The strength of this method is to allow multiple components and factors that may influence the vulnerability level (and subsequent risk level) to be integrated into a numerical scoring system (ISO 2009). Accordingly, applying vulnerability indices to heritage sites provides a ground for the prioritization of different factors influencing vulnerability and, further, for the prioritization of risk treatment strategies in decision-making processes, especially considering resource limitations. Vulnerability or risk index approaches have been applied in the context of cultural heritage (Forino et al. 2016; Ortiz and Ortiz 2016); however, the component of vulnerability and risk and their related indicators have been differently defined depending on the objectives of projects, type of elements at risk, and fields of study. This study proposed a Cultural Heritage Vulnerability Index (CHVI) that encompasses the two following main components:

- Susceptibility or sensitivity: Susceptibility of a heritage site is dependent on its physical characteristics and reflects the performance of its structural and material features to withstand the effects of natural hazards; and
- Coping and adaptive capacities: Coping and adaptive capacities describe the institutional capability of existing heritage conservation and risk management systems at site/local and national levels. Although coping and adaptive capacities are highly interconnected, coping capacity mainly reflects the short/medium-term ability to mitigate, respond to, and cope with sudden-onset hazards, while adaptive capacity comprises the ability to adjust to slow-onset events in a long-term perspective.

3.1 Developing Indicators for Sensitivity/Susceptibility Analysis

Susceptibility analysis is divided into four components that define the parameters and rank the elements that ultimately determine the susceptibility of a given heritage asset to sudden- or slow-onset disasters: structure, materials, immovable elements, and movable elements. For each component of susceptibility, a set of indicators has been developed (Table 1), according to the literature review presented in Sect. 2 while considering the specific characteristics of the study area and similar heritage assets. Subsequently, a set of ranking criteria specific to masonry constructions has been defined for each indicator to score their respective sensitivity (Table 1).

Some particular damage features such as "crack and deformation," may be identified at the structural level—unbalancing the physical properties of the building; or maybe identified at the material level, not necessarily at a stage where the stability of the building is at stake but which influence vulnerability (particularly for slow-onset hazards) and may eventually evolve to cause structural problems. The type of solutions and disciplines dealing with each type of damage sign is different (e.g., engineering for structural issues; conservation-restoration for material issues) and both must be considered. They do not affect susceptibility in the same way, as per the weightings presented in the next section.

The susceptibility of immovable elements (e.g., decorative elements) and movable elements (e.g., collections and archives), besides their specific sensitivity, highly relies on the building structural performance, on the risk mitigation measures for decorative assets and collections, and on the regular maintenance of control systems (e.g., drainage system or light and/or humidity control systems). The existing control system is included in the assessment of coping capacities. The sensitivity of decorative elements and movable objects is scored based on the opinions of site managers and experts, considering first and foremost the type of decay that can be observed in the objects and that should provide the most relevant clues to their sensitivity to different decay agents. Below, an indicative sensitivity ranking matrix is provided (Table 2) for some of the most common heritage materials and decay agents, along with some guidelines to help sensitivity assessments. Table 2 was developed based on the opinions of heritage conservation experts (conservators and conservation scientists involved in the STORM project) in the European project of STORM (Safeguarding Cultural Heritage through Technical and Organisational Resources Management 2016–2019) and rankings were defined from their extensive experience.

3.1.1 Weighting the Susceptibility Indicators

The above-mentioned criteria are not considered equally significant in the overall susceptibility; therefore, they will be weighted by applying the Analytic Hierarchy Process (AHP). Ranking scales for the pairwise comparison of the significance of criteria/indicators are based on a common five "intensity of importance" in AHP: 1, 3, 5, 7, and 9. The AHP, which was originally developed by Saaty and Kearns (1985), is a tool for weighting the assessment criteria in a decision-making process. Tables 3 and 4 shows the procedure of weighting the components contributing to the overall (physical) susceptibility to sudden-onset and slow-onset hazards. The relative significance of the parameters in the overall susceptibility of the pilot sites to disasters has been formulated based on expert opinion. Once the matrix is filled in with the relative importance scores, the weight of each indicator needs to be calculated. For this purpose, each indicator is normalized in its corresponding column; the average

Table 1 Sensitivity/susceptibility indicators and ranking criteria

Susceptibility			
Components	Indicators	Ranking criteria	Sensitivity score
Structure (e.g., load-bearing walls, foundations, roofs, and joints)	Quality of construction (robustness)	Good quality masonry (with well-dressed blocks)	1 (low)
		Medium quality masonry (with irregularly shaped blocks)	2 (medium)
		Rubble masonry	3 (high)
	Type of ground/foundation soil	Bedrock	1 (low)
		Compact granular or clayey soil	2 (medium)
		Alluvial or not compact soil	3 (high)
	Current structural damage and deterioration patterns (structural imbalance): - Open or degraded joints; - Cracks; - Material losses; - Structural deformations; - Biological/vegetation-related structural damages	Rare or no signs; Appropriately repaired/retrofitted	1 (low)
		Some signs present; Poorly repaired/retrofitted	2 (medium)
		Many signs present across large areas	3 (high)
Structural materials (materials used in the load-bearing elements)	Cracks and deformation (e.g., fractures and fissures)	Rare or no signs; Appropriately repaired/restored	1 (low)
		Some signs present; Poorly repaired/restored	2 (medium)
		Many signs present across large areas	3 (high)
	Material detachment (e.g., bursting, crumbling, powdering, and fragmentation)	Same ranking as “Cracks and deformation”	
	Material losses (e.g., erosion and scratch)	Same as “Cracks and deformation”	
	Discoloration and deposit (e.g., moist areas, black crust, and salt crust)	Same as “Cracks and deformation”	
	Biological colonization and vegetation (e.g., lichen, mould, higher plants, and termite attacks)	Same as “Cracks and deformation”	
Immovable elements (e.g., decorative elements)	Material sensitivity of decorative elements, e.g., wall paintings, stuccowork, wood panelling, etc.	See Table 2	
Movable elements (e.g., collections and archives)	Material sensitivity of e.g., collections and archives	See Table 2	

of each row will then be the weight of its corresponding indicator (Saaty and Kearns 1985). The susceptibility score is measured for the two categories of sudden- and slow-onset hazards separately in order to adequately address their contribution to the vulnerability and risks.

Subsequently, the susceptibility levels to sudden- or slow-onset hazards are computed (using the weights obtained above) by the following equation:

$$S_{sudden\ onset\ or\ slow\ onset} = \frac{(SIs \times Ws) + (SIm \times Wm) + (SIi \times Wi) + (SIc \times Wc)}{Ws + Wm + Wi + Wc}$$

where SI = susceptibility components (scored according to Tables 1 and 2); W = weights (Ws, Wm, Wi, and Wc are the weights of components SIs, SIm, SIi, and SIc, respectively); S = susceptibility to sudden-onset or slow-onset disasters.

To analyze the susceptibility indicators, the ranking scores of Low (1), Medium (2), or High (3) are assigned. Susceptibility scores are then reclassified to divide the range of scores into five equal-sized classes with class ranges of 1–1.4, 1.4–1.8, 1.8–2.2, 2.2–2.6, and 2.6–3. This will keep the consistency of the number of the classes in the vulnerability index. These will be respectively interpreted as Very low (1), Low (2), Medium (3), High (4), and Very high (5) susceptibility levels.

Table 2 An indicative sensitivity ranking matrix of heritage materials to environmental threats

Building or decorative materials	Fire	Water	Contaminants (pollutants, salts)	Biological activity	Physical Forces[a]	Radiation	Fluctuations in temperature and relative humidity
A. Artificial stones							
A1. Mortars, plasters, and renders	3	2–3	2–3	1–3	2–3	1–2	1–2
A2. Ceramics	3	1–2	3	1–3	3	1–2	1–2
A3. Glazed ceramics	3	1–2	2–3	1–3	3	1–2	1–2
A4. Earth materials	3	3	2–3	1–3	2–3	1–2	2
A5. Hard hydraulic mortars and concrete	2	1–2	1–2	1–2	2–3	1	1–2
B. Natural stones							
B1. Igneous stones (hard)	2–3	1–2	1–3	1–3	2	1	1–2
B2. Marbles and very dense limestones	3	1–3	2–3	1–3	2	1	1–2
B3. Low-grade metamorphic stones	3	2–3	1–3	1–3	2–3	1	1–3
B4. High porosity sedimentary stones and other soft stones	3	1–3	3	1–3	2–3	1	1–3
C. Organic materials							
C1. Animal origin materials	3	2–3	1–2	2–3	2–3	2–3	1–3
C2. Wood	3	2–3	1–2	2–3	2–3	2–3	1–3
C3. Paper	3	3	1–2	2–3	1–3	2–3	1–3
C4. Other vegetal origin materials	3	3	1–2	2–3	1–3	2–3	1–3
C5. Synthetic organic polymers	3	1–3	1–2	1–3	2–3	2–3	1–3
D. Glass	3	1	3	1–3	3	1–2	1–2
E. Metals	3	1–2	3	1	1–3	1–2	1–3

Source Adapted from STORM Consortium (2017a).

[a] Physical forces include all mechanical stresses that may have an impact on the material.

The rankings above are merely indicative and each case should be carefully analyzed considering its specific environmental and conservation conditions. General guidelines:

- Polychrome surfaces should be marked in the upper values for radiation sensitivity.
- Where ranges are considered, higher values should be chosen for decayed materials; and lower values for sound/stabilized materials.
- The conservation condition of the object may provide hints on its sensitivity to the decay agent in question, particularly instability signs such as: mass loss; deformations, fractures/cracks; presence of salts or other contaminants; corrosion signs; biological colonization damage. Therefore, material susceptibility should be assessed by professionals familiar with the heritage typologies in question.
- In composite objects, overall susceptibility should generally refer to the susceptibility of the prevalent material, but always considering the most susceptible materials (including materials that are not visible).

3.2 Developing Indicators for Coping and Adaptive Capacity Analysis

In the context of cultural heritage, coping and adaptive capacities have not been adequately studied; however, key determinants can be recognized based on the existing relevant literature (Stovel 1998; FEMA 2005; Lagomarsino 2008; UNESCO et al. 2010; Phillips 2015; Michalski and Pedersoli 2016). The indicators to assess coping and adaptive capacities are demonstrated in Table 5. For example, in terms of "Communication and information system," the status of hazard/risk and cultural heritage information system, for example, in GIS and emergency contacts directory (including heritage and disaster specialists) are critical for efficient emergency response. The status of "Risk preparedness" is another example, which is vital to facilitate first aid measures such as salvage, triage, and stabilization and early warning system such as for storm surges. Other important factors influencing the coping and adaptive capacity are human resources (e.g., experienced professionals) and financial resources for risk mitigation and preparedness measures.

The ranking scores assigned to the capacity indicators correspond to the quality level of existing plans/measures: Low 1 (poorly-developed), Medium 2 (acceptable), High 3 (well-developed). Arithmetic mean aggregation method is used to evaluate the overall capacity; no weighting is used since all variables are considered as equally important to the final calculation. The overall score of coping capacity falls into one of the class ranges of 1–1.4, 1.4–1.8, 1.8–2.2, 2.2–2.6, and 2.6–3, respectively interpreted as Very low (1), Low (2), Medium (3), High (4), and Very high (5) capacity levels.

Table 3 Pairwise comparison of the significance of components contributing to the overall susceptibility to sudden-onset hazards

Susceptibility assessment criteria	Structure	Materials	Immovable elements (e.g., decorative elements)	Movable elements (e.g., collections and archives)	Weights	
Structure	1	5	7	9	0.61	Ws
Materials	0.20	1	5	7	0.26	Wm
Immovable elements (e.g., decorative elements)	0.14	0.20	1	3	0.09	Wi
Movable elements (e.g., collections and archives)	0.11	0.14	0.33	1	0.04	Wc
Sum	1.45	6.34	13.33	20	1	

Ws weight of structure, *Wm* weight of materials, *Wi* weight of immovable elements, *Wc* weight of movable elements/collections

Table 4 Pairwise comparison of the significance of components contributing to the overall susceptibility to slow-onset hazards

Susceptibility assessment criteria	Structure	Materials	Immovable elements (e.g., decorative elements)	Movable elements (e.g., collections and archives)	Weights	
Structure	1	0.20	5	7	0.25	Ws
Materials	5	1	7	9	0.60	Wm
Immovable elements (e.g., decorative elements)	0.20	0.14	1	5	0.11	Wi
Movable elements (e.g., collections and archives)	0.14	0.11	0.20	1	0.04	Wc
Sum	6.34	1.45	13.20	22	1	

Ws weight of structure, *Wm* weight of materials, *Wi* weight of immovable elements, *Wc* weight of movable elements/collections

3.3 Vulnerability Calculation: Cultural Heritage Vulnerability Index (CHVI)

While looking at the indicators defined above, a structured questionnaire was designed to evaluate the susceptibility and coping/adaptive capacities. Accordingly, the expert questionnaire was divided into two major sections—susceptibility analysis and coping/adaptive capacity analysis—and each section comprises particular questions corresponding to the respective specific indicators. The experts were asked to evaluate the indicators and rank them according to the ranking system defined in the methodology section.

For susceptibility analysis, the questions were focused on the indicators defined in Table 1, including quality of construction, type of ground/foundation soil, current structural damage and deterioration patterns, discoloration and deposit of materials, biological colonization as well as material sensitivity of decorative elements, and collections and archives based on the ranking criteria in Table 2. For the site of Tróia, the susceptibility assessment questionnaire was under the responsibility of the site manager, supported by stone and archaeology conservation experts. A group of four experts from the management and conservation team in Tróia resort and local conservation experts familiar with the sites ranked the indicators based on an in situ analysis. To analyze the indicators of coping and adaptive capacities, the site manager elicited the assistance of the Portuguese General Directorate of Cultural Heritage (DGPC), as well as of the Grândola Municipality Civil Protection services. The questions explicitly target the indicators defined in Table 5—for example, risk awareness, heritage and hazard information system, legal framework for cultural heritage protection, existing structural and non-structural measures, monitoring and control system, and so on. The components of vulnerability were analyzed according to the ranking scores given by the experts and the methods defined in Sects. 3.1 and 3.2.

The Cultural Heritage Vulnerability Index (CHVI) is performed based on the indicators derived for susceptibility and coping/adaptive capacity. To measure the overall vulnerability, it should be noted that susceptibility and coping/adaptive capacity are opposing components; a higher degree of susceptibility increases the overall vulnerability while a higher degree of coping/adaptive capacity reduces the overall vulnerability. In order to be able to integrate this latter component into the vulnerability index, lack of coping/adaptive capacity needs to be considered instead, which may be calculated by subtracting the coping/adaptive capacity score from four. Finally, vulnerability corresponds to the geometric mean between susceptibility and lack of coping/adaptive capacity, computed through the following equations:

$$V_{sudden\ onset} = S_{sudden\ onset}^{1/2} \times Lack\ of\ coping\ and\ adaptive\ capacities^{1/2}$$

$$V_{slow\ onset} = S_{slow\ onset}^{1/2} \times Lack\ of\ coping\ and\ adaptive\ capacities^{1/2}$$

Table 5 Indicators for assessing coping and adaptive capacities

Coping & adaptive capacities	
Indicators	Ranking criteria
Legal framework and multi-sectoral cooperation	Legal framework for cultural heritage protection from hazards in the legislation related to cultural heritage conservation or civil protection
	Cooperation between disaster management, heritage organizations, and civil protection (for risk preparedness and emergency response)
Risk awareness	Staff awareness of impacts of sudden-onset hazards on cultural heritage
	Staff awareness of impacts of slow-onset hazards on cultural heritage
	Staff awareness regarding climate change threats to cultural heritage
Information and communication system	Heritage information system (e.g., inventory of heritage assets and GIS database)
	Directory of emergency-related contacts (including heritage and disaster specialists)
	Access to early warning and evacuation database/information
	Hazard information system (e.g., GIS hazard database)
	Risk maps (considering both hazard and vulnerability, in the GIS format)
Risk mitigation plan and/or activities	Hazard prevention/mitigation (e.g., levees for flood prevention)
	Structural risk mitigation measures (e.g., seismic structural retrofitting)
	Risk mitigation measures for decorative assets and movable objects (e.g., seismic fixing techniques for collections)
Risk preparedness plan and/or activities	Emergency response services (e.g., equipment and supplies)
	Response plan (e.g., emergency evacuation of movable objects, damage assessment, and security and stabilization)
	Disaster drills and field exercises within the site
	Early warning systems for sudden-onset disasters (e.g., fire alarms and storm warning)
	Human resources (e.g., experience professionals)
Monitoring and maintenance plans and procedures	Regular monitoring and maintenance of structures/materials
	Regular maintenance of control systems (e.g., drainage system or light and/or humidity control systems)
	Regular monitoring of environmental parameters (e.g., monitoring of humidity levels)
	Regular monitoring of climate change parameters (e.g., sea-level rise)
Socioeconomic factors related to risk management	Insurance (life insurances excluded)
	Financial resources for risk management (e.g., for risk mitigation and post-disaster recovery)
	Local community support for protection of cultural heritage (e.g., local volunteers during emergency response)

4 Study Area: The Roman Ruins of Tróia

The Roman Ruins of Tróia in Portugal are located on the estuarine shore of a peninsula between the Sado River estuary and the Atlantic Ocean, with archaeological structures stretching along 2 km (Fig. 1). The site is heavily affected by the marine and estuarine environments. River discharge fluctuates strongly, therefore the ocean greatly influences the estuary, with most of the basin behaving as a coastal lagoon with reduced freshwater influence. Locally generated waves and semi-diurnal tides with large amplitudes and strong tidal currents along the site are responsible for coastal erosion (Andrade et al. 2013; Silveira et al. 2014). Tróia has very dry summers and more humid winters with on average 24 heavy precipitation days per year.

In Roman times, the settlement specialized in the production of salted fish and fish sauces and was the largest of its kind in the Roman Empire. It was active from the first century to the fifth century CE, but its occupation continued at least until the sixth century (Pinto et al. 2014). The remains of 27 fish-salting workshops are visible, some quite well preserved (Case 1a), while others, located on the shoreline, are very affected by tide currents (Case 1b). There is also a bath complex (Case 2), a residential area (Case 3), a Mausoleum cemetery (Case 4), a Mensa tomb cemetery (Case 5), a Mausoleum (Case 6), an Early Christian basilica with surrounding buildings (Case 7), and a concentration of structures on the shoreline known as Roman harbor (Case 8) located on the site. The site was designated as a National Monument in 1910, with a *non aedificandi* area and buffer zone. An identification record

Fig. 1 The northwestern area of the Roman ruins on the right bank of the Peninsula of Tróia, *Source* Tróia Resort. Reprinted with permission

for the heritage cases in Tróia was prepared to be used in the susceptibility analysis of the site (Fig. 2). Further information about the other cases can be obtained from the reports of the STORM project (STORM Consortium 2017b, 2017c).

Following the development of a hazard taxonomy and its application to the case studies in Ravankhah et al. (2019a), it revealed that the study area is exposed to diverse sudden-onset hazards (e.g., earthquakes, tsunamis, landslides, wind-generated waves, and coastal floods) and slow-onset hazards (e.g., coastal erosion, tides, saline spray, and colonization (by microorganisms, higher plants, and pests). High-tide/storm combinations will yield higher than usual tides, largely increasing the odds of stone loss and eventual wall collapsing at the shoreline structures. The intensity of heavy rainfall at the site is projected to increase due to climate change (Ravankhah et al. 2019b); this may, for example, cause the sliding of the large sand dune pressuring against the tallest remaining shoreline wall; dune instability caused by ongoing coastal erosion favors this process.

5 Results: Application of the Methodology to Tróia

While applying the proposed methodology of vulnerability assessment, the components of vulnerability were analyzed according to the ranking scores given by the experts in the questionnaire and the methods defined in Sects. 3.1, 3.2, and 3.3. Below, the indicator-based vulnerability assessment of Tróia to sudden- and slow-onset hazards according to the information obtained from the questionnaire is presented.

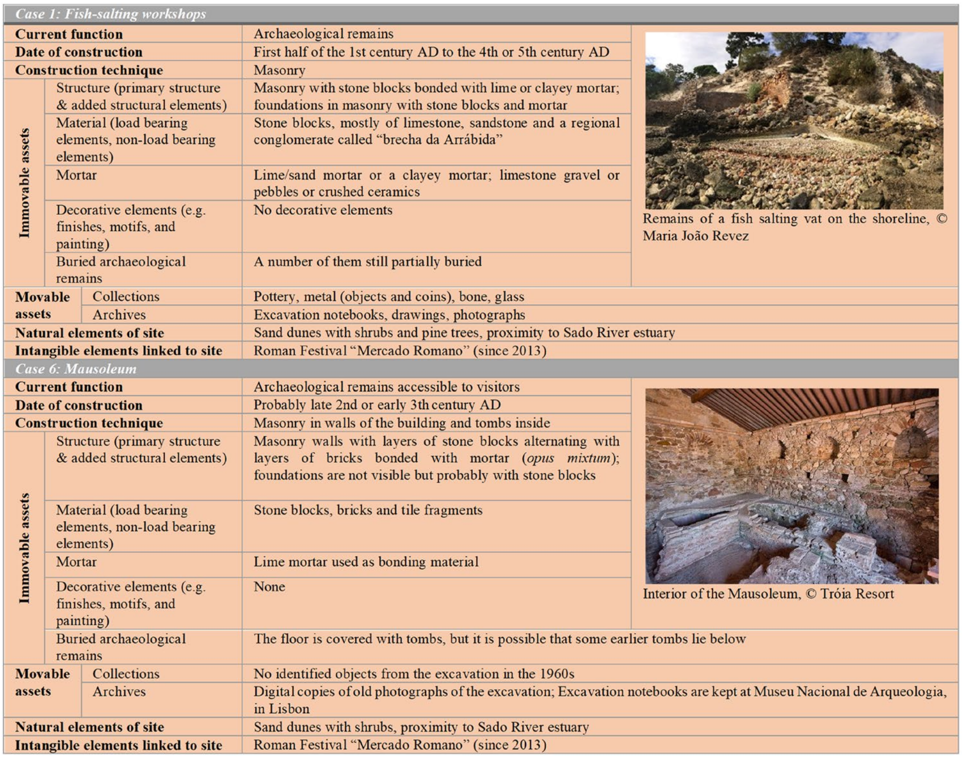


Fig. 2 Examples of identification records for heritage cases in Tróia. Photos reprinted with permission

Case 1: Fish-salting workshops			
Current function		Archaeological remains	Remains of a fish salting vat on the shoreline, © Maria João Revez
Date of construction		First half of the 1st century AD to the 4th or 5th century AD	
Construction technique		Masonry	
Immovable assets	Structure (primary structure & added structural elements)	Masonry with stone blocks bonded with lime or clayey mortar; foundations in masonry with stone blocks and mortar	
	Material (load bearing elements, non-load bearing elements)	Stone blocks, mostly of limestone, sandstone and a regional conglomerate called "brecha da Arrábida"	
	Mortar	Lime/sand mortar or a clayey mortar; limestone gravel or pebbles or crushed ceramics	
	Decorative elements (e.g. finishes, motifs, and painting)	No decorative elements	
	Buried archaeological remains	A number of them still partially buried	
Movable assets	Collections	Pottery, metal (objects and coins), bone, glass	
	Archives	Excavation notebooks, drawings, photographs	
Natural elements of site		Sand dunes with shrubs and pine trees, proximity to Sado River estuary	
Intangible elements linked to site		Roman Festival "Mercado Romano" (since 2013)	
Case 6: Mausoleum			
Current function		Archaeological remains accessible to visitors	Interior of the Mausoleum, © Tróia Resort
Date of construction		Probably late 2nd or early 3th century AD	
Construction technique		Masonry in walls of the building and tombs inside	
Immovable assets	Structure (primary structure & added structural elements)	Masonry walls with layers of stone blocks alternating with layers of bricks bonded with mortar (*opus mixtum*); foundations are not visible but probably with stone blocks	
	Material (load bearing elements, non-load bearing elements)	Stone blocks, bricks and tile fragments	
	Mortar	Lime mortar used as bonding material	
	Decorative elements (e.g. finishes, motifs, and painting)	None	
	Buried archaeological remains	The floor is covered with tombs, but it is possible that some earlier tombs lie below	
Movable assets	Collections	No identified objects from the excavation in the 1960s	
	Archives	Digital copies of old photographs of the excavation; Excavation notebooks are kept at Museu Nacional de Arqueologia, in Lisbon	
Natural elements of site		Sand dunes with shrubs, proximity to Sado River estuary	
Intangible elements linked to site		Roman Festival "Mercado Romano" (since 2013)	

5.1 Susceptibility Analysis

Susceptibility analysis entailed a semi-quantitative expert assessment of the indicators listed in Table 1, following an on-site survey where the physical features of the different structures were scored in accordance with the ranking criteria. All archaeological structures in Tróia stand on sandy or otherwise not compact soil, and, while some are confined, many are stand-alone or are only partially confined. In terms of robustness, being an industrial site means that several elements were built on irregular stone masonry, with ceramic pieces embedded in the joints, smoothed and protected using coarse lime renders; the exception being the Bath complex, in regular masonry with marble cladding. Most structures are only one story high, with only a few walls preserving their original two-story height.

In terms of conservation condition, there is a stark contrast between the relative absence of structural damage in the main visiting area, which comprises the core part of the site and has been kept relatively sheltered or otherwise protected and which has been the focus of regular conservation efforts for the past decades (Cases 1a, 2, 3, 4, 5, 6, 7), and the many structural deterioration signs spread across large areas of the elements standing in the Sado River shoreline, easily accessible to passers-by and to the impacts of tidal action (Cases 1b, 8). At the material level, most structures were considered to present some susceptibilities in need of addressing, largely due to the mortar system condition, displaying serious lack of cohesion, as well as material losses, in many areas, particularly in the structures along the Sado River shoreline (Cases 1b, 8), and due to the presence of biological colonization and higher plants.

Figure 3 demonstrates the assessment of susceptibility indicators for the use cases of the site. The indicators support the identification of hotspots in different use cases. For example, the Early Christian Basilica is suffering from cracks and detachments and biological colonization. The bar chart in fact emphasizes the different determinants of sensitivity that need to be considered within vulnerability and risk reduction.

5.2 Coping and Adaptive Capacity Analysis

The result of the structured questionnaire for evaluating the coping and adaptive capacity indicators is illustrated in Fig. 4. The site of Tróia currently faces difficulties related to the lack of institutional/legal provisions for the disaster risk management of cultural heritage sites, which is still very far from being the current practice in Portugal. Nevertheless, the site is well documented and mapped, its information system has been regularly updated, and there are protocols with the civil protection services in place for personal safety that could potentially be developed for cultural heritage protection. In terms of hazard information, there are GIS data available for most identified sudden-onset hazards, although

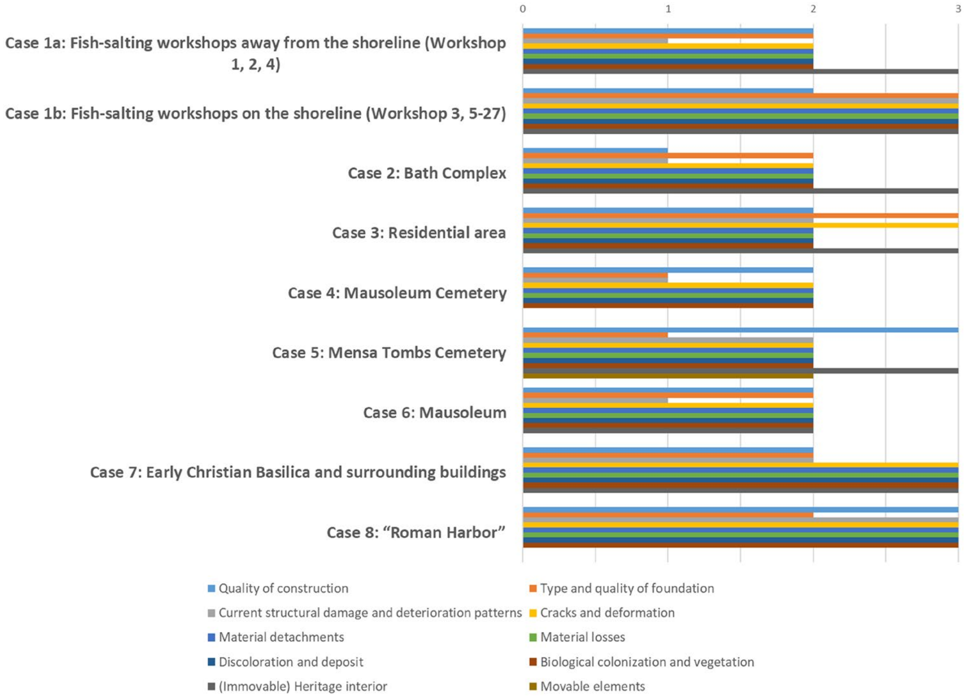


Fig. 3 Analysis of the susceptibility indicators in Tróia

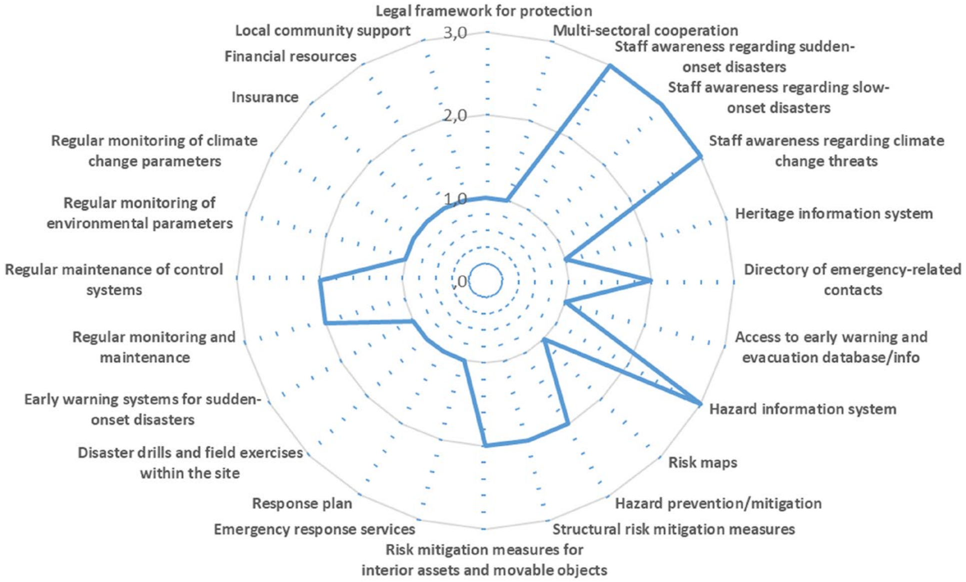


Fig. 4 Analysis of the coping/adaptive capacity indicators for Tróia

information is lacking on slow-onset hazards. Regarding risk mitigation activities, as mentioned, there have been significant conservation efforts over the past decades that allowed the stabilizing of many archaeological structures, for example:

- in Case 1a, conservation works to consolidate and stabilize the Roman structures;
- in Case 1b, some fish-salting workshops have been protected by a beach re-nourishment;
- in Case 3, shoring and partial reburying of a structure to prevent dune pressure;
- in Case 7, all the floors have been protected by cloth and a layer of sand for protection from intense rainfall. The floors exposed to natural elements were protected with vegetation-proof cloth and plastic cover.

Participating in the European project of STORM was decisive in raising the risk awareness of several stakeholders at the Tróia site, but the staff has been aware of natural hazard- and climate change-related risks for much longer, as since very early on authors mentioned the threat of coastal erosion on the site (Barreiros 1561), albeit preparedness plans or drills specific to cultural heritage are still limited to those performed in the scope of the project. Nevertheless, great care is dedicated to the regular monitoring and maintenance of the archaeological structures, particularly the most valuable ones (Cases 1a, 2, 3, 4, 5, 6, 7).

5.3 Overall Vulnerability

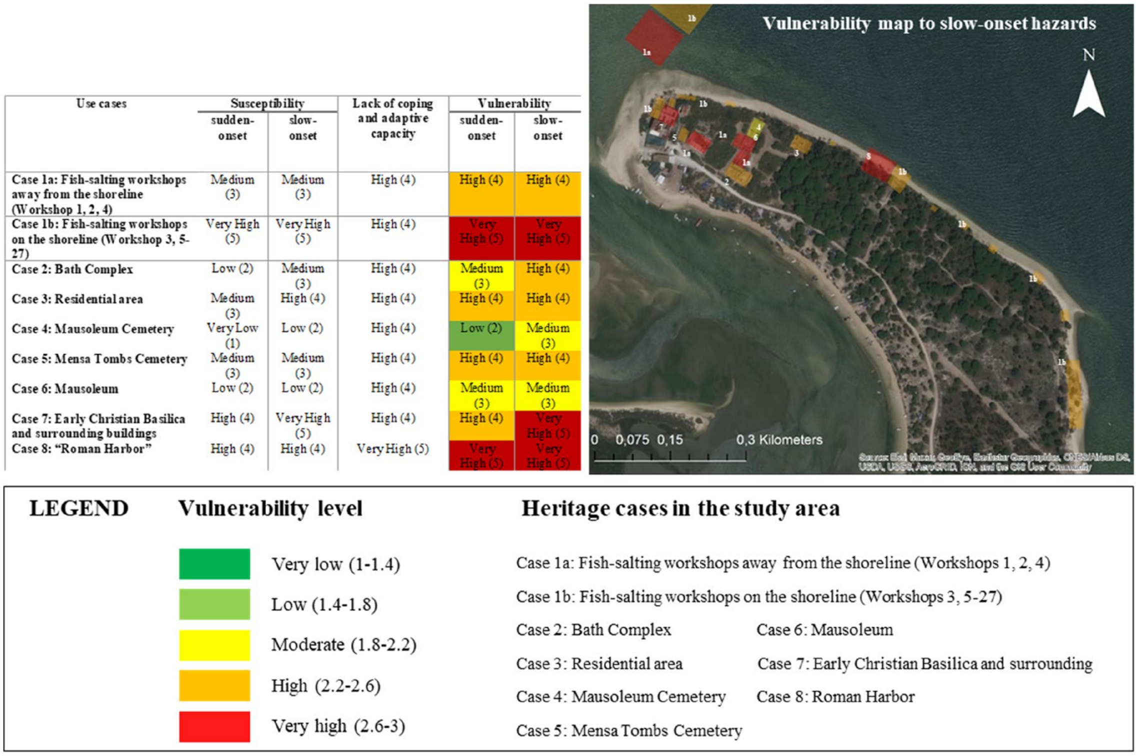
The overall vulnerability was calculated by multiplying the susceptibility of the different site cases by the lack of coping/adaptive capacity value, using the equations in Sect. 3.3. As Fig. 4 shows, vulnerability of the site to the two categories of sudden-onset and slow-onset hazards is calculated according to the CHVI.

The vulnerability score may fall in one of the five equal-sized classes with class ranges of 1–1.4, 1.4–1.8, 1.8–2.2, 2.2–2.6, and 2.6–3. They are respectively interpreted by numbers and color codes as Very low (1, dark green), Low (2, light green), Medium (3, yellow), High (4, orange), and Very high (5, red) levels. According to the vulnerability index, vulnerability maps for the two categories of sudden- and slow-onset hazards were generated to illustrate the level of vulnerability of different heritage cases in Tróia. Figure 5 shows an example of a map for slow-onset hazards.

The findings highlight the vulnerability levels of the heritage cases that need specific considerations in vulnerability reduction. For determining concrete measures, one should go back to the indicators of susceptibility and coping/adaptive capacities that were analyzed in the assessment procedure. The vulnerability scores will further contribute to prioritization of the site's areas for risk treatment strategies, for example, based on the tolerability of risks. However, this needs to be carried out based on an integrated assessment of the risk components, that is, hazard, exposure, and vulnerability.

6 Discussion and Conclusions

The proposed framework provides a vulnerability assessment that addresses sensitivity at the building/site level as well as coping and adaptive capacities at site and regional/national level. Such an integrated approach is vital for



Use cases	Susceptibility		Lack of coping and adaptive capacity	Vulnerability	
	sudden-onset	slow-onset		sudden-onset	slow-onset
Case 1a: Fish-salting workshops away from the shoreline (Workshop 1, 2, 4)	Medium (3)	Medium (3)	High (4)	High (4)	High (4)
Case 1b: Fish-salting workshops on the shoreline (Workshop 3, 5-27)	Very High (5)	Very High (5)	High (4)	Very High (5)	Very High (5)
Case 2: Bath Complex	Low (2)	Medium (3)	High (4)	Medium (3)	High (4)
Case 3: Residential area	Medium (3)	High (4)	High (4)	High (4)	High (4)
Case 4: Mausoleum Cemetery	Very Low (1)	Low (2)	High (4)	Low (2)	Medium (3)
Case 5: Mensa Tombs Cemetery	Medium (3)	Medium (3)	High (4)	High (4)	High (4)
Case 6: Mausoleum	Low (2)	Low (2)	High (4)	Medium (3)	Medium (3)
Case 7: Early Christian Basilica and surrounding buildings	High (4)	Very High (5)	High (4)	High (4)	Very High (5)
Case 8: "Roman Harbor"	High (4)	High (4)	Very High (5)	Very High (5)	Very High (5)

LEGEND

Vulnerability level

🟩	Very low (1-1.4)
🟩	Low (1.4-1.8)
🟨	Moderate (1.8-2.2)
🟧	High (2.2-2.6)
🟥	Very high (2.6-3)

Heritage cases in the study area

Case 1a: Fish-salting workshops away from the shoreline (Workshops 1, 2, 4)
Case 1b: Fish-salting workshops on the shoreline (Workshops 3, 5-27)
Case 2: Bath Complex
Case 3: Residential area
Case 4: Mausoleum Cemetery
Case 5: Mensa Tombs Cemetery
Case 6: Mausoleum
Case 7: Early Christian Basilica and surrounding
Case 8: Roman Harbor

Fig. 5 Vulnerability assessment and maps for the two categories of sudden- and slow-onset hazards

providing a holistic view of vulnerability, not only for reducing the direct damages of hazards, but also to enhance the capacity of the management system to prevent secondary hazards and human errors and enable emergency response and short- and long-term recovery. The findings emphasize which determinants of sensitivity (e.g., quality of construction and existing deterioration patterns) and coping capacities (such as risk and hazard information systems and the existing monitoring and maintenance) need to be particularly incorporated into vulnerability and risk reduction strategies.

The proposed method mainly targets cultural heritage sites, particularly large-scale sites, to provide a vulnerability assessment of the different areas of a site to multiple hazards and facilitate risk management at the site level. When applying the method to other similar cases, the criteria and indicators might need slight modifications according to the material, structural and non-structural attributes of a site, geological and sociocultural characteristics, and the institutional and management systems. This method does not easily lend itself to the risk analysis of decorative elements and collections alone—namely because there might be problems, for example, radiations for a wall painting that do not necessarily pose problems for the whole building. For museums, for instance, specific quantitative methods exist to analyze the structural system and collections/archives (Muething et al. 2005; Lowry et al. 2007).

The output of the vulnerability assessment provides preventive conservation managers with a prioritization of heritage elements and measures for structural sensitivity reduction and capacity building. However, there are other factors that influence the level of risks and, accordingly, the prioritization of treatment measures for the elements of a site. These factors are the types of significant hazards or climate events and the heritage values of a site, which are beyond the scope of vulnerability. The interrelations between the risk components are critical when it comes to the application of vulnerability assessment to "risk assessment and management of cultural heritage" (Ravankhah et al. 2019a, p. 358). The measure of vulnerability does not include a weighting for the relative value of a heritage asset or the degree to which that value will be diminished by any estimated physical losses (Daly 2014). Accordingly, a full picture of risk assessment needs to look at all components of risk, that is, hazard, exposure, and vulnerability while assessing multiple values of cultural heritage sites.

Reducing structural susceptibility is an effective option to reduce risk. The interventions, however, should not result in the loss or impairment of the authenticity and integrity of the historical property. Where new materials and reinforcement techniques are proposed, these should be compatible with those already existing, and be durable and reversible, as far as it is practicable. Continuous monitoring and maintenance is essential for the early detection of damage or change to the heritage asset. The effectiveness of mitigation, response, and recovery plans highly rely on the quality of heritage and disaster documentation in advance, in particular in an online heritage and risk information system. To avoid a high level of chaos during emergencies, when cultural heritage can be exposed to inappropriate (even if well-meaning) or even deliberately offensive actions damaging the site, a well-planed "Cultural First Aid" (Tandon 2018) can help to secure and stabilize endangered elements during a complex emergency and to avoid secondary losses.

The first key criterion to promote coping and adaptive capacities is raising risk awareness. Admittedly, capacity building and training should be addressed through cross-sectoral educational and training programs among a wide range of stakeholders engaged in the planning and implementation of risk preparedness strategies. This will further facilitate establishing a legal framework for the adequate incorporation of cultural heritage into the existing disaster management systems and multi-sectoral cooperation. The availability of long-term funding and resource allocation requires such a legal framework supporting this approach.

Overall, vulnerability assessment will further enable determining priorities and developing risk mitigation and preparedness measures, in particular reducing structural sensitivity and promoting coping capacities. The assessment framework and its corresponding indicators facilitate the integration of cultural heritage into disaster risk management and climate change adaptation plans at the city and regional levels. Further research is needed to develop applicable qualitative and quantitative approaches on how structural and non-structural factors of vulnerability can be solidly addressed in the risk assessment and management framework for cultural heritage.

Acknowledgments This article is based on the Safeguarding Cultural Heritage through Technical and Organisational Resources Management (STORM) project, funded by the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement no. 700191. The authors would like to express their heartfelt thanks to Dr. José Delgado Rodrigues for his support in the vulnerability assessment section. We would also like to thank the STORM Consortium, in particular the Portuguese General Directorate of Cultural Heritage (DGPC) and the Município de Grândola – Serviço Municipal de Proteção Civil (SMPC), for their support in the data collection process. The article reflects only the authors' views. The European Union is not liable for any use that may be made of the information contained herein.

References

Andrade, C., L. Rebêlo, P.O. Brito, and M.C. Freitas. 2013. Holocene processes: Aspects of the geology, geomorphology and sediment dynamics of the Tróia-Sines coastal stretch (*Processos holocénicos: Aspectos da geologia, geomorfologia e dinâmica sedimentar do troço litoral Tróia-Sines*). In *Geology of Portugal in the Iberian context (Geologia de Portugal no contexto da Ibéria)*, ed. R. Dias, A. Araújo, P. Terrinha, and J.C. Kullenberg, 533–571. Lisbon: Sociedade Geológica de Portugal e Universidade de Évora (in Portuguese).

Appiotti, F., V. Assumma, M. Bottero, P. Campostrini, G. Datola, P. Lombardi, and E. Rinaldi. 2020. Definition of a risk assessment model within a European Interoperable Database Platform (EID) for cultural heritage. *Journal of Cultural Heritage* 46: 268–277.

Baldi, P., A. Giovagnoli, M. Marabelli, and R. Coppi. 1995. Models and methods for the construction of risk maps for cultural heritage. *Journal of the Italian Statistical Society* 4: 1–15.

Barreiros, G. 1561. Chorography of some places by a path that Gaspar Barreiros took in the year 1591 beginning in the city of Badajoz, in Castile, until that of Milan in Italy (*Chorographia de alguns lugares que stam em hum caminho, que fez Gaspar Barreiros ó anno MDxxxxj começado na cidade de Badajoz em Castella, te á de Milam em Italia*). Coimbra, Portugal: Ioam Alvarez, impressor da universidade (in Portuguese).

Berto, L., A. Doria, P. Faccio, A. Saetta, and D. Talledo. 2017. Vulnerability analysis of built cultural heritage: A multidisciplinary approach for studying the Palladio's Tempietto Barbaro. *International Journal of Architectural Heritage* 11(6): 773–790.

Birkmann, J., ed. 2013. In *Measuring vulnerability to natural hazards: Towards disaster resilient societies*. Tokyo: United Nations University Press.

Birkmann, J., O.D. Cardona, M.L. Carreño, A.H. Barbat, M. Pelling, S. Schneiderbauer, S. Kienberger, and M. Keiler et al. 2013. Framing vulnerability, risk and societal responses: The MOVE framework. *Natural Hazards* 67(2): 193–211.

Bogardi, J., and J. Birkmann. 2004. Vulnerability assessment: The first step towards sustainable risk reduction. In *Disaster and society: From hazard assessment to risk reduction*, ed. D. Malzahn, and T. Plapp, 75–82. Berlin: Logos Verlag.

Brooks, N. 2003. *Vulnerability, risk and adaptation: A conceptual framework*. Tyndall Centre for Climate Change Research working paper No. 38. University of East Anglia, Norwich, UK.

Cantagallo, C., E. Spacone, D. Perrucci, N. Liguori, and C. Verazzo. 2020. A multilevel approach for the cultural heritage vulnerability and strengthening: Application to the Melfi Castle. *Buildings* 10(9): Article 158.

Cardona, O.D. 2013. The need for rethinking the concepts of vulnerability and risk from a holistic perspective: A necessary review and criticism for effective risk management. In *Mapping vulnerability: Disasters, development and people*, ed. G. Bankoff, G. Frerks, and D. Hilhorst, 56–70. London: Routledge.

Cardona, O.D., M.K. Van Aalst, J. Birkmann, M. Fordham, G. Mc Gregor, P. Rosa, R.S. Pulwarty, and E.L.F. Schipper et al. 2012. Determinants of risk: Exposure and vulnerability. In *Managing the risks of extreme events and disasters to advance climate change adaptation: Special report of the Intergovernmental Panel on Climate Change*, 65–108. Cambridge: Cambridge University Press.

D'Ayala, D., A. Copping, and H. Wang. 2006. A conceptual model for multi-hazard assessment of the vulnerability of historic buildings. In *Structural analysis of historical constructions: Possibilities of numerical and experimental techniques. Proceedings of the Fifth International Conference*, 6–8 November 2006, ed. P.B. Lourenço, P. Roca, C. Modena, and S. Agrawal, 121–140. New Delhi, India, Barcelona, Spain: CIMNE.

Daly, C. 2014. A framework for assessing the vulnerability of archaeological sites to climate change: Theory, development, and application. *Conservation and Management of Archaeological Sites* 16(3): 268–282.

FEMA (Federal Emergency Management Agency). 2005. *Integrating historic property and cultural resource considerations into hazard mitigation planning: How-to guide (FEMA 386–9)*. Washington: FEMA.

Figueiredo, R., X. Romao, and E. Pauperio. 2021. Component-based flood vulnerability modelling for cultural heritage buildings. *International Journal of Disaster Risk Reduction* 61: Article 102323.

Fitzner, B. 2007. Evaluation and documentation of stone damage on monuments. In *Proceedings of the International Symposium of Stone Conservation*, 29 May 2007, Seoul, Korea, 25–30.

Forino, G., J. MacKee, and J. von Meding. 2016. A proposed assessment index for climate change-related risk for cultural heritage protection in Newcastle (Australia). *International Journal of Disaster Risk Reduction* 19: 235–248.

Füssel, H.M., and R.J.T. Klein. 2006. Climate change vulnerability assessments: An evolution of conceptual thinking. *Climatic Change* 75(3): 301–329.

Gallopín, G.C. 2006. Linkages between vulnerability, resilience, and adaptive capacity. *Global Environmental Change* 16(3): 293–303.

Garrote, J., A. Diez-Herrero, C. Escudero, and I. Garcia. 2020. A framework proposal for regional-scale flood-risk assessment of cultural heritage sites and application to the Castile and León region (central Spain). *Water* 12(2): Article 329.

ICOMOS-ISCS (International Council on Monuments and Sites—International Scientific Committee for Stone). 2008. *Illustrated glossary on stone deterioration patterns*. Paris: ICOMOS-ISCS. http://iscs.icomos.org/glossary.html. Accessed 10 May 2017.

IPCC (Intergovernmental Panel on Climate Change). 2014. Annex II: Glossary. In *Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*, ed. Core Writing Team, R.K. Pachauri, and L.A. Meyer, 117–130. Geneva: IPCC.

IPCC (Intergovernmental Panel on Climate Change). 2018. Annex I: Glossary. In *Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, ed. V. Masson-Delmotte, p. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, et al., 541–562. Cambridge: Cambridge University Press.

ISO (International Organization for Standardization). 2009. *IEC 31010:2009 risk management—Risk assessment techniques*. Geneva: ISO.

Jurgilevich, A., A. Räsänen, and S. Juhola. 2021. Assessing the dynamics of urban vulnerability to climate change: Case of Helsinki, Finland. *Environmental Science & Policy* 125: 32–43.

Kelman, I. 2018. Lost for words amongst disaster risk science vocabulary?. *International Journal of Disaster Risk Science* 9(3): 281–291.

Lagomarsino, S. 2006. On the vulnerability assessment of monumental buildings. *Bulletin of Earthquake Engineering* 4: 445–463.

Lagomarsino, S. 2008. Vulnerability assessment of historical buildings. In *Assessing and managing earthquake risk: Geo-scientific and engineering knowledge for earthquake risk mitigation: Developments, tools, techniques*, ed. C.S. Oliveira, A. Roca, and X. Goula, 135–159. Dordrecht: Springer.

Lowry, M., B.J. Farrar, D. Armendariz, and J. Podany. 2007. Protecting collections in the J. Paul Getty Museum from earthquake damage. *WAAC Newsletter* 29(3): 16–23.

Michalski, S., and J.L. Pedersoli. 2016. *The ABC method: A risk management approach to the preservation of cultural heritage*. Rome: ICCROM (International Centre for the Study of the Preservation and Restoration of Cultural Property), Canadian Conservation Institute. http://publications.gc.ca/collections/collection_2017/pch/CH44-157-2016-eng.pdf. Accessed 15 May 2017.

Muething, G., R. Waller, and F. Graham. 2005. Risk assessment of collections in exhibitions at the Canadian museum of nature. *Journal of the American Institute for Conservation* 44(3): 233–243.

Ortiz, R., and P. Ortiz. 2016. Vulnerability index: A new approach for preventive conservation of monuments. *International Journal of Architectural Heritage* 10(8): 1078–1100.

Papathoma-Köhle, M., B. Gems, M. Sturm, and S. Fuchs. 2017. Matrices, curves and indicators: A review of approaches to assess physical vulnerability to debris flows. *Earth-Science Reviews* 171: 272–288.

Phillips, H. 2015. The capacity to adapt to climate change at heritage sites—The development of a conceptual framework. *Environmental Science & Policy* 47: 118–125.

Pinto, I.V., A.P. Magalhães, and p. Brum. 2014. An overview of the fish-salting production centre at Tróia (Portugal). In *Fish & ships: Production et commerce des salsamenta durant l'Antiquité*, ed. E. Botte, and V. Leitch, 145–157. Aix-en-Provence: Centre Camille Jullian, Éditions Errance.

Podestà, S., and C. Romano. 2014. A macroseismic method for vulnerability assessment of Rationalist architectural heritage. *Procedia Economics and Finance* 18: 173–180.

Quattrone, G. 2016. Risk analysis and vulnerability assessment of archaeological areas for the preventive conservation. In *Digital heritage: Progress in cultural heritage: Documentation, preservation, and protection*, ed. M. Ioannides, 157–168. Cham: Springer.

Ravankhah, M., R. de Wit, A.V. Argyriou, A. Chliaoutakis, M.J. Revez, J. Birkmann, M. Žuvela-Aloise, and A. Sarris et al. 2019. Integrated assessment of natural hazards, including climate change's influences, for cultural heritage sites: The case of the historic centre of Rethymno in Greece. *International Journal of Disaster Risk Science* 10(3): 343–361.

Ravankhah, M., R. de Wit, M.J. Revez, A. Chliaoutakis, A.V. Argyriou, I. Vaz Pinto, P. Brum, and M. Žuvela-Aloise et al. 2019. Risk assessment and risk management for the protection of cultural heritage. In *Cultural heritage resilience against climate change and natural hazards: Methodologies, procedures, technologies and policy improvements achieved by Horizon 2020–700191 STORM project*, ed. V. Resta, A.B. Utkin, F.M. Neto, and C.Z. Patrikakis, 55–88. Pisa: Pisa University Press.

Rodríguez-Rosales, B., D. Abreu, R. Ortiz, J. Becerra, A.E. Cepero-Acán, M.A. Vázquez, and p. Ortiz. 2021. Risk and vulnerability assessment in coastal environments applied to heritage buildings in Havana (Cuba) and Cadiz (Spain). *Science of the Total Environment* 750: Article 141617.

Romao, X., E. Pauperio, and N. Pereira. 2016. A framework for the simplified risk analysis of cultural heritage assets. *Journal of Cultural Heritage* 20: 696–708.

Saaty, T.L., and K.P. Kearns. 1985. *Analytical planning: The organization of systems*. New York: Pergamon Press.

Salazar, L.G.F., X. Romao, and E. Pauperio. 2021. Review of vulnerability indicators for fire risk assessment in cultural heritage. *International Journal of Disaster Risk Reduction* 60: 102286.

Schneiderbauer, S., E. Calliari, U. Eidsvig, and M. Hagenlocher. 2017. The most recent view of vulnerability. In *Science for disaster risk management 2017: Knowing better and losing less*, ed. K. Poljanšek, M. Ferrer, T. De Groeve, and I. Clark, 68–82. EUR 28034 EN. Luxembourg: Publications Office of the European Union.

Sesana, E., A.S. Gagnon, C. Bertolin, and J. Hughes. 2018. Adapting cultural heritage to climate change risks: Perspectives of cultural heritage experts in Europe. *Geosciences* 8(8): Article 305.

Sevieri, G., C. Galasso, D. D'Ayala, R. De Jesus, A. Oreta, M.E.D.A. Grio, and R. Ibabao. 2020. A multi-hazard risk prioritization framework for cultural heritage assets. *Natural Hazards and Earth System Sciences* 20(5): 1391–1391.

Silveira, T., F. Andrade, I. Vaz Pinto, A. Patrícia Magalhães, and V. Cabedal. 2014. Beach filling to protect the Roman ruins of Tróia: Project and archaeological monitoring (*Enchimento de praia para protecção das ruínas romanas de Tróia: Projecto e acompanhamento arqueológico*). *Setúbal Arqueológica* 15: 259–304.

STORM Consortium. 2017a. D5.3—Risk management guidelines. Project STORM—Safeguarding cultural heritage through technical and organisational resources management. https://cordis.europa.eu/project/id/700191/results. Accessed 16 Jan 2023.

STORM Consortium. 2017b. D3.1—STORM use cases and scenarios. Project STORM—Safeguarding cultural heritage through technical and organisational resources management. https://cordis.europa.eu/project/id/700191/results. Accessed 16 Jan 2023.

STORM Consortium. 2017c. D5.1—Risk assessment and management methodology. Project STORM—Safeguarding cultural heritage through technical and organisational resources management. https://cordis.europa.eu/project/id/700191/results. Accessed 16 Jan 2023.

Stovel, H. 1998. *Risk preparedness: A management manual for world cultural heritage*. Rome: ICCROM (International centre for the study of the preservation and restoration of cultural property). http://www.iccrom.org/ifrcdn/pdf/ICCROM_17_RiskPreparedness_en.pdf. Accessed 15 May 2017.

Tandon, A. 2018. *First aid to cultural heritage in times of crisis, Vol. II: Toolkit for coordinated emergency preparedness and response to secure tangible and intangible heritage*. Rome: ICCROM (International Centre for the Study of the Preservation and Restoration of Cultural Property) and Amsterdam: Prince Claus Fund for Culture and Development.

Tarbotton, C., F. Dall'osso, D. Dominey-Howes, and J. Goff. 2015. The use of empirical vulnerability functions to assess the response of buildings to tsunami impact: Comparative review and summary of best practice. *Earth-Science Reviews* 142: 120–134.

Tolles, E.L., E.E. Kimbro, and W.S. Ginell. 2002. *Planning and engineering guidelines for the seismic retrofitting of historic adobe structures*. Los Angeles: Getty Conservation Institute.

Turner, B.L., R.E. Kasperson, P.A. Matson, J.J. McCarthy, R.W. Corell, L. Christensen, N. Eckley, and J.X. Kasperson et al. 2003. A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academy of Sciences* 100(14): 8074–8079.

UNESCO, ICCROM, ICOMOS, and IUCN (United Nations Educational, Scientific and Cultural Organization, International Centre for the Study of the Preservation and Restoration of Cultural Property, International Council on Monuments and Sites, and International Union for Conservation of Nature). 2010. *Managing disaster risks for World Heritage*. Paris: UNESCO. http://whc.unesco.org/uploads/activities/documents/activity-630-1.pdf. Accessed 16 Jan 2023.

UNISDR (United Nations International Strategy for Disaster Reduction). 2015. *Proposed updated terminology on disaster risk reduction: A technical review*. Geneva: The United Nations Office for Disaster Risk Reduction. www.preventionweb.net/files/45462_backgoundpaperonterminologyaugust20.pdf. Accessed 10 Jan 2017.

Wisner, B., P. Blaikie, T. Cannon, and I. Davis. 2004. *At risk: Natural hazards, people's vulnerability and disasters*, 2nd edn. London: Routledge.

Zschau, J. 2017. Where are we with multihazards, multirisks assessment capacities? In *Science for disaster risk management 2017: Knowing better and losing less*, ed. K. Poljanšek, M. Marin Ferrer, T. De Groeve, and I. Clark, 98–130. EUR 28034 EN. Luxembourg: Publications Office of the European Union.