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Multi-risk analysis on European cultural and natural UNESCO heritage sites

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Abstract
A multi-criteria risk analysis to identify and to rank the most critical UNESCO World Heritage Sites (WHSs) in Europe was implemented in the framework of the JPI-CH PROTHEGO project. The presented approach considers three natural geo-hazards (i.e. landsliding, seismic shaking and volcanic activity) for which homogenous European hazard maps are available. The methodology is based on a quantitative and reproducible heuristic assessment of risk through the development of a new UNESCO Risk Index (URI), which combines the level of hazard with a potential damage vector. The latter expresses the expected level of damage as a function of the type of heritage site (monuments, cultural routes, rock-art sites, cultural landscapes, earthworks/hominid sites, walls and natural sites), the position with respect to the ground (underground or overground) and the hazard type. The methodology was applied both to the entire WHS site and to the different properties that compose the site, with the purpose of identifying areas, inside the same site, with different level of risk. At European scale, the spatial distribution of risk reflects the fact that only three hazards were implemented in the analysis so far, with highest values in the Mediterranean area due to the importance of seismic hazard.

Keywords UNESCO WHSs · Natural hazard · Risk assessment · Europe · Hazard ranking

1 Introduction

UNESCO World Heritage Sites (hereafter referred as WHSs) protection and conservation are very important to communicate to future generations the human impact on Earth and the beauty of the Earth itself. WHSs are defined as cultural and natural heritage. Cultural heritage sites are monuments, groups of buildings, sites that are of outstanding universal

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value from the point of view of history, art or science (UNESCO World Heritage Centre 2017). Natural heritage sites are natural features, geological and physiographical formations and natural areas of outstanding universal value from the point of view of science, conservation or natural beauty (UNESCO World Heritage Centre 2017).

Inevitably WHSs are affected by multiple factors and problems emerge from a combination of pressures such as development and infrastructure (~65% of properties); mismanagement and legal issues (~67% of properties); other human activities (~44% of properties); natural events and disasters (~22% of properties); other issues (~19% of properties) (Wijesuriya et al. 2013).

Hence, natural events and disasters are the main category of pressure on heritage, not directly related to human activities. Consequently, assessing natural hazard and evaluating the expected risk in these areas are of paramount importance for management and conservation of these sites (Taboroff 2000; Waller 2003; Delmonaco et al. 2005; Leask and Fyall 2006; Lollino and Audisio 2006; Paolini et al. 2012; Sabbioni et al. 2010; Spizzichino et al. 2013). In the literature, a number of guiding principles were suggested both to reduce the risks on World Heritage properties from natural and human made disasters and provide a methodology to identify, assess and mitigate disaster risks (e.g. ICCROM UNESCO and IUCN ICOMOS2010; Michalski and Pedersoli 2017), to improve the management plans and the integration of hazard and risk in cultural heritage (e.g. Stovel 1998; Taboroff 2000, 2003; ICCROM UNESCO and IUCN ICOMOS 2010; Michalski and Pedersoli 2017). Pavlova et al. (2017) presented a global-scale analysis of geological hazards at World Heritage Sites. Reimann et al. (2018) developed an index-based approach that allows for ranking WHSs at risk from coastal flooding and erosion due to sea-level rise in the Mediterranean region. Recently, Valagussa et al. (2020) evaluated the reliability of UNESCO Periodic Reports for the assessment of hazards affecting the heritage sites and to rank the most critical WHSs in Europe through multi-criteria analysis.

When assessing hazard and evaluating risk, in a multi-risk approach as in this case, there are some elements to bear in mind (Margottini and Menoni 2018):

(1) Different types of natural events require different intensity scales for hazard assessment;
(2) Quantitative risk assessment combines hazard, exposure, vulnerability and type of element at risk. The outcome is based on the choice of a coherent scale of investigation for the risk components. This is even more relevant for a multi-risk problem;
(3) A regional evaluation for a multi-risk problem requires the harmonisation of various intensity scales, the adoption of a reference topographic scale and classification units suitable to provide the most reliable outcome, for the given purpose;
(4) The scale of final representation is not the same as the scale of assessment, which is determined by the lowest spatial resolution of used data sets and the chosen methodology (i.e. methods of hazard assessment include different approaches such as deterministic, probabilistic, scenarios, indicators, process modelling, time-dependent and time-independent. All these methods are grouped into two main categories: forecast—or projection—and prediction).

Specific methodologies and spatial resolutions have been identified in hazard assessment, suggesting three different strategic approaches, corresponding to four different scales (Delmonaco et al. 2003, 2006; Margottini and Menoni 2018): the regional strategic approach (scale > 50,000); the local general approach which exhibits two stages such as the general or preparatory land-use plan (scale 1:5000–1:50,000) and the second detailed land-use plan (scale 1:500–1:5000); and the site engineering approach (scale 1:100–1:1000).

In the present work, we provided an overview of hazard assessment at European scale for three different phenomena (earthquake, landslide and volcanic eruption), then comparing such hazards with exposed heritages for which local topographic data was digitised and collected within the PROTHEGO project (PROTection of European Cultural HEritage from GeO-hazards, available at https://www.prothego.eu/). The final accuracy is a regional strategic approach, clearly depending on the spatial resolution adopted in hazard assessment, more than the scale of representation for exposed elements. Such an overview may be useful to characterise the hazards that actually affect the sites and to rank sites based on risk. This ranking may help UNESCO to provide international assistance and co-operation in scientific, artistic and technical terms, and to prioritise the interventions and/or to establish a management plan and set up a reporting system on the state of conservation of heritage sites based on the associated level of risk.

This research aims at presenting a continental-scale analysis, based on the available and existing data. However, a brief overview of the available and existing data highlights the impossibility to perform a rigorous probabilistic hazard and risk assessment at such scale, due to heterogeneity and incompleteness of the hazard data, and the difficulty to quantify vulnerability level at European scale. This is especially true for some hazards, such as landslides, whose processes are limited in size, thus, requiring a local-scale methodology.

At European scale, different projects have been developed to assess the risk associated with natural hazards. Among others, the DDRM (France) multi-risk approach (DRM-Délégation aux Risques Majeurs 1990); the EC TIGRA project 1997 (Delmonaco et al. 1999); the TEMRAP (The European Multi-Hazard Risk Assessment Project) (Delmonaco et al. 2003); the ESPON 2005 multi-hazard approach (Schmidt-Thomé, 2005); the JRC—Multi-risk Approach: an integrated assessment of weather-driven natural risk in Europe (Barredo et al. 2005); the ARMONIA Project (Delmonaco et al. 2006) can be mentioned. In addition, international approaches were developed: the methodology of Disaster Management in Tajikistan (Granger 2001); FEMA (Federal Emergency Management Agency) multi-risk approach (United States, Federal Emergency Management Agency 2003); the Geoscience Australia methodology (Dwyer et al. 2004); the Global Risk Analysis Impact-weighted multi-hazard disaster hotspot index (Dilley 2005); the Mamdani fuzzy methodology (Yanar et al. 2020). Other works are referred in the literature such as the PRIM Project (Lari et al. 2009); the New Zealand RiskScape developed by GNS Science and NIWA (Gallina et al. 2016); the CAPRA project (Gallina et al. 2016).

In this paper, we applied a simplified multi-risk analysis at European scale considering multiple hazards with the objective of ranking the risk of WHSs in Europe. In addition, this approach was implemented and verified, at local scale, for those hazards for which reliable data are available.

2 WHSs data set in Europe

A spatial database was implemented by the collection of vector geographic layers provided by local authorities and open data catalogues (39%; mainly from Italy, the United Kingdom, Belgium, Finland, Cyprus, Spain, UNEP-WCMC World Database on Protected Areas) and by digitising of UNESCO documentation (Spizzichino et al. 2016, Fig. 1a). In this geodatabase, both the property zones (which can be made up by more than one part

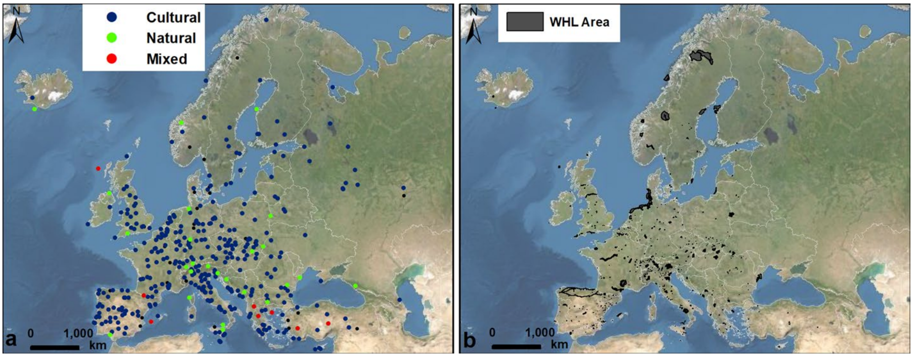

Fig. 1 **a** WHSs inside the European continent at May 2016; **b** Sites boundaries of the WHL (Spizzichino et al. 2016)

for each specific WHS) and the buffer zones of each property of the WHS were mapped as polygons (Fig. 1b). The property (i.e. cultural or natural property) is the site nominated and inscribed inside the World Heritage List (Fig. 2). The buffer zone is an area surrounding the nominated property, which is functionally important as a support to the property and its protection (UNESCO World Heritage Centre 2017) (Fig. 2). The data set consists of 399 WHS polygons listed in 2016 in Europe (Spizzichino et al. 2016), and it does not include Russia, Ukraine, Belarus and Moldova (Fig. 1a). It is interesting to observe that most of the WHSs are composed of more than one property (see Fig. 2a, b), sometimes located in

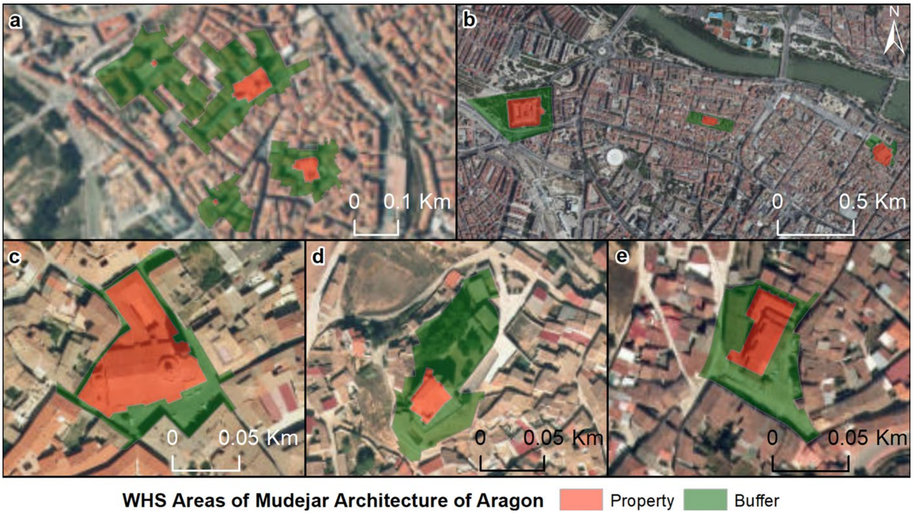

Fig. 2 Example of property and buffer zones for the WHS area of Mudejar architecture of Aragon (Spain). **a** Teruel Catedral, Torre techumbre y cimborrio declarados Patrimonio Mundial Clarification, Torre de San Martin Clarification, Torre de El Salvador Clarification, Teruel Iglesia de San Pedro Clarification, Abside, claustro y torre de colegiata de Santa María, Calatayud, and Abside, parroquieta y cimborrio de La Seo; **b** Abside, parroquieta y cimborrio de La Seo, Restos mudéjares de palacio de la Aljafería, and Torre e iglesia parroquial de San Pablo; **c** Abside, claustro y torre de colegiata de Santa María; **d** Iglesia parroquial de Santa Tecla; and **e** Iglesia de Santa María

different countries (transboundary sites; e.g. Struve Geodetic Arc or Primeval Beech Forests of the Carpathians and the Ancient Beech Forests of Germany).

3 Multi-risk analysis: an integrated approach

In the framework of the JPI-CH PROTHEGO project, a method to identify and to rank the most critical WHSs on the basis of available European-scale hazard maps was developed. The method is based on a quantitative heuristic analysis, which was preferred over probabilistic or deterministic approaches due to the lack of homogeneous information on the probability of occurrence of hazard and the impossibility to assess vulnerability or fragility of heritage sites at continental scale.

The UNESCO Risk Index (URI) associated with each WHS was defined as:

$$\mathrm{URI} = \sum_{1}^{n} \mathrm{PDV}_i * \mathrm{PH}_i \tag{1}$$

where PDV_i is the potential damage vector of the ith hazard, and PH_i is the potential hazard level of the ith hazard. URI is linearly rescaled from 0 to 1 with respect to the highest possible risk for a hypothetical site with the highest potential damage and hazard.

3.1 Potential damage vector (PDV)

The potential damage in response to the different natural hazards depends on different characteristics of the WHS at risk, but mostly on the typology (e.g. buildings vs cultural routes, Table 1) and the position with respect to ground (i.e. above or under-ground, Table 1). The typology of cultural heritage site was reclassified starting from the International Council on Monuments and Sites (Jokilehto et al. 2005) (Table 1), whereas the natural heritage sites were considered separately. For each typology and each position, a potential damage score related to a specific hazard was assigned by expert knowledge following a relative

Table 1 Classification of the WHSs and associated potential damage score for the three considered hazards

Category	Description	Potential damage score		
		Earthquake	Landslide	Volcano
TYP (type)	Monument/building/built area	5	4	4
	Cultural route	2	4	3
	Rock-art site	3	4	4
	Cultural landscape, park and garden	2	4	4
	Earthwork/burial mound/hominid site	2	4	4
	Walls	3	4	4
	Natural	1	1	1
POS (position with respect to ground level)	Underground	2	3	2
	Overground	4	3	4

Damage scores range from 1 (i.e. very low) to 5 (i.e. very high). POS refers to the position with respect to the ground level. Underground sites are mines, caves and underground buildings scale from 1 (i.e. very low) to 5 (i.e. very high) (Table 1). A panel of 16 experts from partner institutions of the JPICH PROTHEGO project was involved, mainly in the fields of engineering and engineering geology. The potential damage scores were elicited from a panel of experts involved in the PROTHEGO project through a questionnaire. In order to compare the potential damages among the different hazards, the experts were asked to judge, for each hazard, the potential damage deriving from events with a magnitude corresponding to the same return period (i.e. 100 years for all the hazards). Finally, the modal value of the scores was adopted.

Based on the above scores, a potential damage vector (PDV), combining the effects of typology and position, here considered as two independent dimensions of the potential damage, was defined as:

$$\text{Potential Damage Vector(PDV)} = \sqrt{\text{TYP}^2 + \text{POS}^2} \quad (2)$$

where TYP and POS are the typological and positional damage scores, respectively (Table 1). This vector represents a qualitative description of vulnerability of the WHS.

3.2 Identification of the potential hazard (PH)

For this analysis at continental scale, only three hazards were considered since they offer a consistent, homogeneous and reliable cover over Europe: earthquake, landslides and volcanoes (Spizzichino et al. 2016). For earthquakes, the European Seismic Hazard Map (European seismic hazard model, EPEHR, (Woessner et al. 2015), a result of the SHARE probabilistic seismic hazard assessment, was used (Fig. 3a). The European Seismic Hazard Map is based on a time-independent, probabilistic approach. Three different earthquake rate models were assembled from available data, reflecting the state-of-the-art knowledge on (1) past moderate to large earthquakes combined in a single European Earthquake Catalogue (SHEEC), (2) fault structures and subduction zone models and (3) the rate of deformation

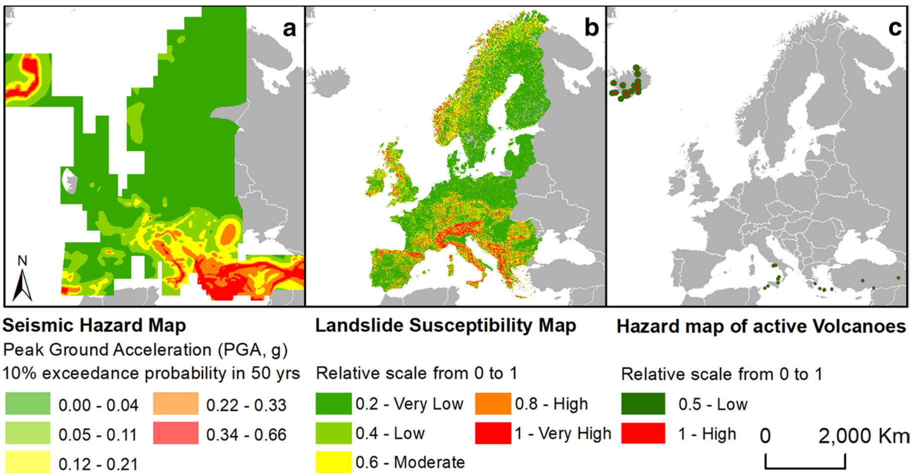

Fig. 3 European-scale hazard maps used for the analysis: **a** Seismic Hazard Map (European seismic hazard model, EPEHR, Woessner et al. 2015); **b** European Landslide Susceptibility Map (ELSUS1000, Günther et al. 2014a, b); **c** Hazard map of active Volcanoes in Europe (Loughlin et al. 2015)

of the Earth crust as observed by global positioning systems. The models were then combined with the ground motion prediction equations (GMPE) and calibrated for the SHARE strong ground motion database (Woessner et al. 2015). The European Seismic Hazard Map (scale 1:1,000,000) displays the ground motion (i.e. the Peak Ground Acceleration, PGA) expected to be exceeded with a 10% probability in 50 years, corresponding to a return period of 475 years. The map extends from the Mid-Atlantic Ridge to the East European Platform, from the subduction zones in the Mediterranean and the large transform faults in Turkey to the Baltic shield (Woessner et al. 2015). For landslides, the European Landslide Susceptibility Map (ELSUS1000) with a cell size of 1000 × 1000 m (Günther et al. 2014a, b) was considered (Fig. 3b). The map shows levels of spatial probability of landslide occurrence at continental scale, including all types of landslides. The map was produced by regionalising the study area based on elevation and climatic conditions, followed by spatial multi-criteria evaluation modelling using European slope gradient, soil material and land cover spatial data sets as the main landslide conditioning factors (Günther et al. 2014a, b). For volcanoes, the hazard map of active volcanoes in Europe (Fig. 3c, Loughlin et al. 2015) was adopted. For each volcano, two buffer zones were defined: an area with high hazard associated with the area supposedly affected by lava, pyroclastic flows, tephra and volcanic ash, and an area with low hazard associated with the maximum propagation of the volcanic ash only (https://annuario.isprambiente.it/) at scale 1:100,000. This distinction is based on the characteristics, location and available technical literature of each volcano. For the analysis, the potential hazard was calculated, for each hazard and within each site, as the areal-weighted average of the map values linearly rescaled between 0 and 1 (0 = no hazard; 1 = max value in Europe, assuming that the continent includes areas where each hazard reaches maximum possible values).

3.3 UNESCO Risk Index for the WHSs

To calculate the risk index, the potential hazard was calculated for each WHS as the weighted average within the entire area of the site, which sometimes is represented by various polygons. To be conservative, the potential damage vector associated with the WHSs composed of properties of different typology (e.g. the Routes of Santiago de Compostela: Camino Francés and Routes of Northern Spain is composed of four routes and 16 buildings) is the highest among all the parts of the properties.

The UNESCO Risk Index for the European WHSs is shown in Fig. 4, while the most at-risk sites are listed in Table 2. Southern Europe results the area with the highest risk on the basis of the three considered hazards. This clearly reflects the typologies of hazard considered for this study and their distribution over Europe.

The archaeological areas of Pompeii, Herculaneum and Torre Annunziata is the most at risk cultural site in Europe. This site was affected by the Vesuvius eruption on 79 AD (Pliny the Younger) (e.g. Sigurdsson et al. 1982) and successively affected by other eruptions, the last one in March 1944. In addition, in February 2015, heavy rains triggered a small scar failure, with the collapse of a retaining wall, leading to a partial-closure of the site to the public. Regarding seismic hazard, the main seismic event that affected the cities of Pompeii and Herculaneum occurred on 2 February, 62 AD (e.g. Marturano 2006). This earthquake event caused damages to the nearby city of Naples, which is the second most at risk cultural site in Europe. In its history, Naples has been affected by numerous earthquakes with a magnitude higher than 5.5 which caused damage to monuments, churches, buildings and, sometimes, loss of lives (CPTI15) (Rovida et al. 2016). The third most at

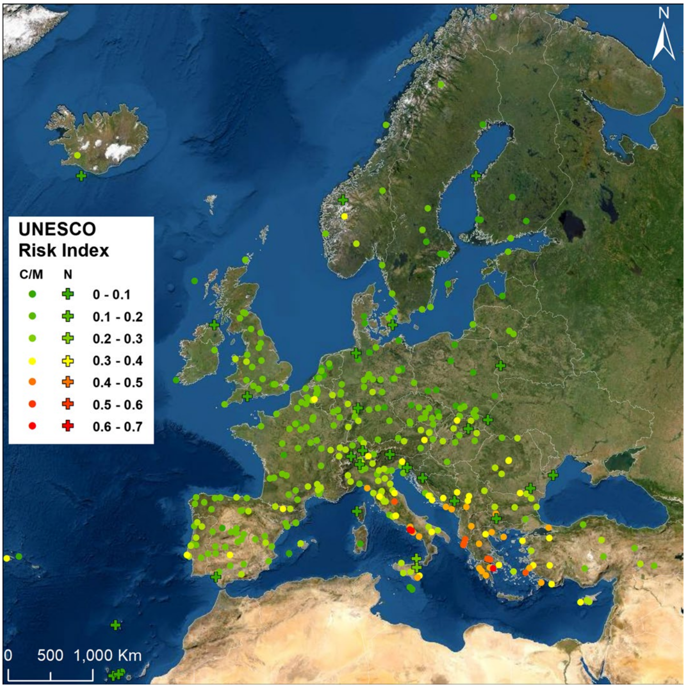

Fig. 4 Risk ranking of the URI values according to the 399 WHSs based on the multi-criteria methodology. The sites were subdivided into cultural and mixed sites (C/M—dot) and natural sites (N—cross). The values are linearly rescaled between 0 and 1 on the basis of the highest possible risk

risk cultural site is the Sanctuary of Asklepios at Epidaurus, in Greece, which was hit by destructive earthquakes on 522 and 551 AD.

Figure 5 shows the distribution of the UNESCO Risk Index in the states listed in 2016 in Europe both for cultural and mixed WHSs and Natural WHSs (see also supplementary material Figure S1, S2 and S3 for the distribution of the each considered hazard). This confirms how Italy and Greece have the largest number of sites subject to highest risk based on earthquakes, volcanoes and landslides.

3.4 UNESCO Risk Index for the properties of the WHSs

As mentioned before, most of the WHSs are composed of more than one part, and some of these parts are sometimes located in different countries and are also of different typology. To allow the definition of different levels of risk within each WHS, and to separate multi-sites grouped into single-one, we applied this methodology to each part of the property of a WHS site. 2351 properties were identified within the 399 European UNESCO sites to which hazard and risk levels were associated (Figs. 6 and 7). This spatially detailed analysis allows us to discriminate among parts of the same site. For instance, the site-portion most at risk in Europe, Herculaneum, is significantly more at risk with respect to Pompei and Torre Annunziata that belong to the same site. This is due to a higher proximity to Vesuvius volcano and a higher seismic hazard (Fig. 7c). For Naples, significant differences can be observed among the different parts, mostly due to the landslide hazard (Fig. 7b).

Table 2 Ten WHSs with the highest potential risk in Europe, defined through the multi-risk analysis

Type	Rank	Site name	State name	URI
Cultural and mixed site	1	Archaeological areas of Pompei, Herculaneum and Torre Annunziata	Italy	0.682
	2	Historic Centre of Naples	Italy	0.680
	3	Sanctuary of Asklepios at Epidaurus	Greece	0.621
	4	Late Baroque Towns of the Val di Noto (South-Eastern Sicily)	Italy	0.586
	5	Eighteenth century Royal Palace at Caserta with the Park, the Aqueduct of Vanvitelli and the San Leucio Complex	Italy	0.545
	6	Historic Centres of Berat and Gjirokastra	Albania	0.533
	7	Monasteries of Daphni, Hosios Loukas and Nea Moni of Chios	Greece	0.529
	8	Costiera Amalfitana	Italy	0.528
	9	Butrint	Albania	0.526
	10	Archaeological Site of Delphi	Greece	0.523
Natural Site	1	Mount Etna	Italy	0.148
	2	Isole Eolie (Aeolian Islands)	Italy	0.139
	3	Pirin National Park	Bulgaria	0.075
	4	Skocjan Caves	Slovenia	0.073
	5	Swiss Alps Jungfrau-Aletsch	Switzerland	0.060
	6	The Dolomites	Italy	0.060
	7	Surtsey	Iceland	0.060
	8	Srebarna Nature Reserve	Bulgaria	0.057
	9	Durmitor National Park	Montenegro	0.057
	10	Swiss Tectonic Arena Sardona	Switzerland	0.055

The sites are divided into cultural and mixed sites, and natural sites. The value of URI was normalised by the highest possible value identified with the methodology

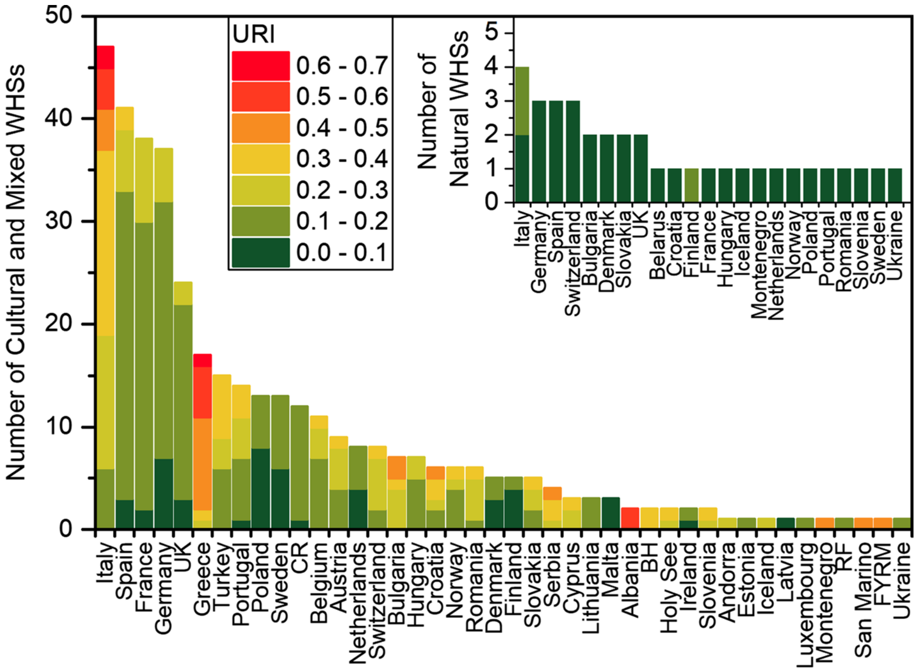

Fig. 5 Distribution of the UNESCO Risk Index inside each state, for cultural and mixed WHSs (large bar plot) and natural WHSs (upper right hand inset). The states are ordered based on the number of WHSs

The number of properties for each WHS ranges between 1 and 705, where the maximum is observed for the Rock Art of the Mediterranean Basin on the Iberian Peninsula (Spain). In Figs. 8 and 9, the distribution for the property risk index is taken into account with a threshold equal to or greater than 10 properties and greater than one property for cultural/mixed and natural WHSs, respectively. In particular, especially for cultural and mixed WHSs, a range of variation of the risk index inside each site is observed. This difference is related to the spatial positioning of each property with respect to the spatial distribution of the considered hazards. Due to the relatively low number of properties for each Natural WHS, the variation is less evident.

4 Discussion

The heuristic method proposed in this work for the characterisation of risk affecting the WHSs in Europe is simple enough to be applicable at European scale, consistently. Even if this approach does not allow to assess risk on a probabilistic and monetary basis, it allows a comparison and ranking of WHSs, in order to probabilistically prioritise sites, according to their exposure to selected natural hazards. At the same time, the proposed approach fully exploits the available information covering homogeneously the European area.

The approach implemented for the characterisation of the potential damage is very simple. Ideally, the potential damage should be calculated as a function of the intensity of the hazard, in terms of vulnerability or fragility curves. However, such curves are currently

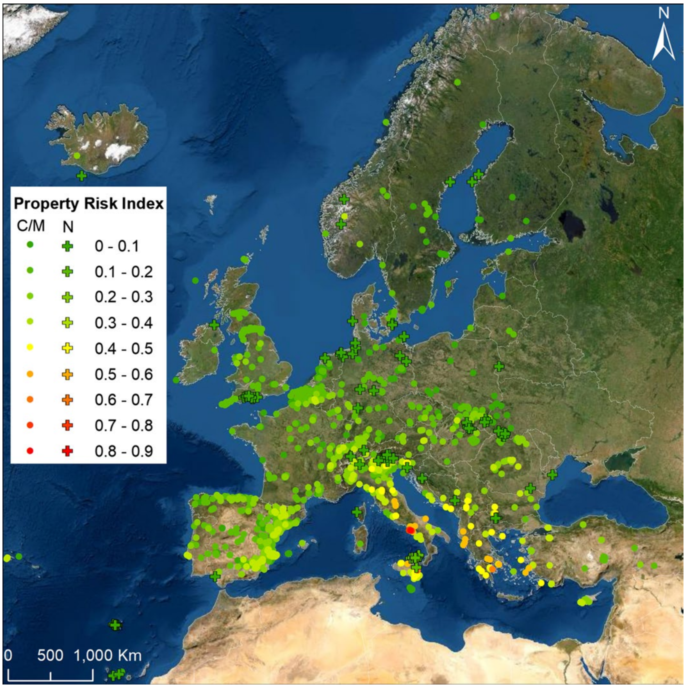

Fig. 6 Risk ranking of the 2,351 WHS property parts based on the multi-criteria methodology. The sites were divided into cultural and mixed sites (C/M—dot) and natural sites (N—cross). The values were linearly rescaled between 0 and 1 on the basis of the highest possible risk

available only for some of the hazards (e.g. seismic, flood) and a few building or structure typologies. Therefore, it was not possible to integrate such rigorous approach in this analysis.

The potential damage vector depends only on a rough classification of heritage typology (TYP) and the WHSs position (POS). While this approach represents an improvement with respect to other simpler approaches (Taboroff 2000), it does not account for other factors that may control the potential damage such as the type of material used, the size and the structural characteristics of the building and the state of conservation. Unfortunately, complete reliable data on such factors are still lacking for all the European WHSs, thus hampering their use in the analysis. Five out of the ten sites with the highest level of risk (Table 2) are located in Italy, and Mount Etna results the most at-danger natural WHS in Europe. Seismic hazard dominates, at the moment, the distribution of the risks, with highest risk in the Mediterranean area. This distribution (Figs. 4 and 5) is not fully realistic and reflects the fact that only three hazards were accounted for the analysis so far (see also supplementary material Figure S1, S2 and S3). Moreover, seismic and volcanic hazards are strongly related to each other due to tectonics, thus amplifying the risk level in the tectonically active Mediterranean area. A more realistic representation will be attained by incorporating other significant risks, such as floods and storms as soon as they will become available at European scale.

Considering the distribution of the risk inside the European states, it is observed from Fig. 5 that Italy is one of the most affected state. All 47 cultural and mixed WHSs in Italy

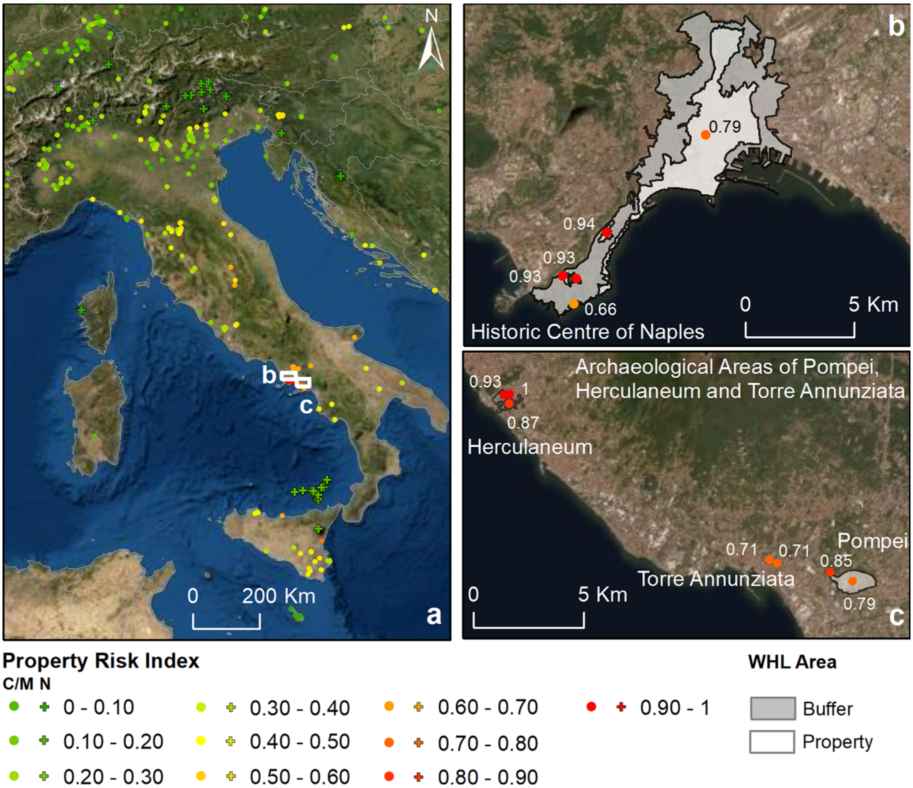

Fig. 7 **a** Risk ranking of the Italian WHS property parts. **b** Detail of the risk level inside the Historic Centre of Naples, and **c** Archaeological areas of Pompei, Herculaneum and Torre Annunziata. The Historic Centre of Naples shows a high level of risk in the SW portion of the site with respect to the NE portion. The Herculaneum properties show a higher level of risk with respect to Pompei and the Torre Annunziata properties. The values are linearly rescaled between 0 and 1 on the basis of the highest value of the method

show different levels of risk based on the considered hazards. Supplementary material figure S1 shows that Italy, Greece and Turkey are the most affected by earthquakes. On the basis of the landslide susceptibility map, almost all states are affected by the landslide hazard. Unfortunately some states, such as Turkey, are not covered by the landslide susceptibility map; for this reason, the columns in figure S2 (supplementary material) are dark green. Regarding volcanic hazard, from supplementary material figure S3, it is shown that only three states have cultural and mixed WHSs (Italy, Greece and Portugal).

Focusing on natural WHSs, we observe that their number is very limited and that the only state to present all three hazards is Italy. Data sets that could be introduced in a near future in the analysis are 1—flood hazard, in accordance with the European floods directive (Directive 2007/60/EC) that is addressed to the assessment and management of flood risk in EU Member States. 2—Storm hazard, with increasing information reported, for example, within the European Severe Weather Database (Dotzek et al. 2009). 3—Tsunami hazard, starting from the European tsunamis catalogue, which contains 290 tsunamis generated in the European and Mediterranean seas since 6150 BC (Maramai et al. 2014). 4—Subsidence hazard, based on InSAR data (Ferretti et al. 2000), with a possible coverage of

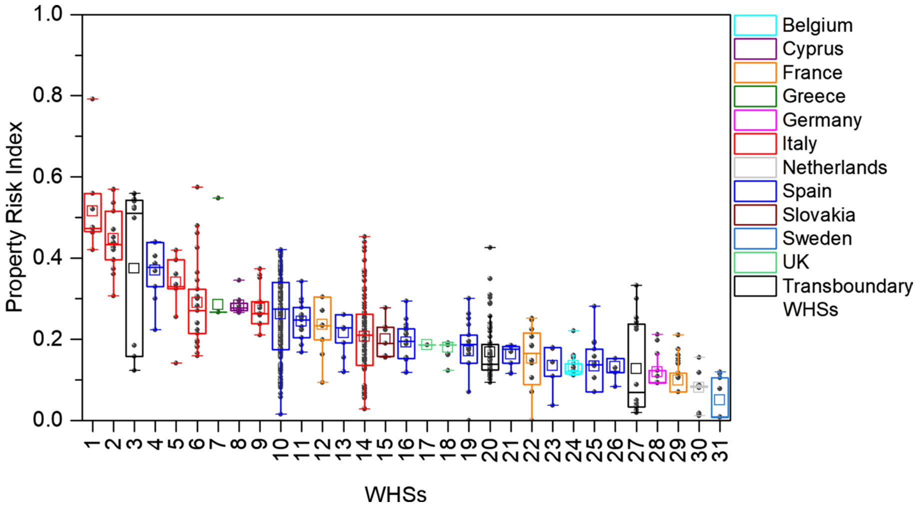

Fig. 8 Distribution of UNESCO Risk Index inside each property for cultural and mixed WHSs with a property number equal to or greater than 10. Grey dots represent the properties. 1—Late Baroque Towns of the Val di Noto (South-Eastern Sicily); 2—City of Vicenza and the Palladian Villas of the Veneto; 3—Medici Villas and Gardens in Tuscany; 4—Heritage of Mercury. Almadén and Idrija; 5—Paleochristian and Byzantine Monuments of Thessalonika; 6—Prehistoric Pile dwellings around the Alps; 7—Catalan Romanesque Churches of the Vall de Boí; 8—Belfries of Belgium and France; 9—Rock Art of the Mediterranean Basin on the Iberian Peninsula; 10—Historic Centre of Rome, the Properties of the Holy See in that City Enjoying Extraterritorial Rights and San Paolo Fuori le Mura; 11—Residences of the Royal House of Savoy; 12—Painted Churches in the Troodos Region; 13—Cave of Altamira and Paleolithic Cave Art of Northern Spain; 14—Wooden Tserkvas of the Carpathian Region in Poland and Ukraine; 15—Prehistoric Sites and Decorated Caves of the Vézère Valley; 16—Routes of Santiago de Compostela: Camino Francés and Routes of Northern Spain; 17—Prehistoric Rock Art Sites in the Côa Valley and Siega Verde; 18—Champagne Hillsides, Houses and Cellars; 19—Wooden Churches of the Slovak part of the Carpathian Mountain Area; 20—Archaeological Ensemble of Tárraco; 21—Fortifications of Vauban; 22—Flemish Béguinages; 23—Classical Weimar; 24—Nord-Pas de Calais Mining Basin; 25—Cornwall and West Devon Mining Landscape; 26—Frontiers of the Roman Empire; 27—Mudejar architecture of Aragon; 28—Archaeological Ensemble of Mèrida; 29—Defence Line of Amsterdam; 30—Old Town of Ávila with its Extra-Muros Churches; 31—Naval Port of Karlskrona

all the European UNESCO sites. For subsidence, only 37% of the European UNESCO sites is currently covered by existing InSAR data sets (Cigna and Tapete 2017). The potential to cover the WHSs exists via the processing of SAR data available from the archives of the various space agencies, such as ERS, ENVISAT and Sentinel-1 C-band data from ESA or RADARSAT-1/2 data from the Canadian Space Agency (CSA), Xband COSMO-SkyMed data from the Italian Space Agency (ASI) or TerraSAR-X data from the German Aerospace Center (DLR), or L-band ALOS-1/2 data from the Japanese Space Agency (JAXA).

To improve the spatial resolution of the analysis, the same methodology was applied also to each property of each site with the purpose of identifying areas, inside the same site, with different level of risk. On a national scale, this allows each state to identify single monuments/buildings/historic centres that need greater attention and protection within complex WHSs. This analysis can be a valuable tool for the plan of intervention and monitoring at each UNESCO site for the local administrators, especially if the site is characterised by a high spatial extent. Figure 8 shows a large scatter of the risk index values thus highlighting how the value identified through URI, while being a useful element for the

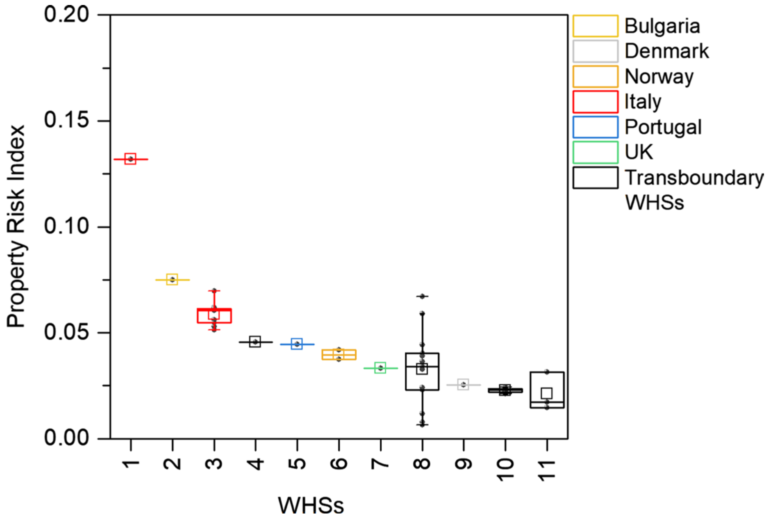

Fig. 9 Distribution of UNESCO Risk Index inside each property for Natural WHSs with more than 1 property. Grey dots represent the properties. 1—Isole Eolie (Aeolian Islands); 2—Pirin National Park; 3—The Dolomites; 4—Caves of Aggtelek Karst and Slovak Karst; 5—Laurisilva of Madeira; 6—West Norwegian Fjords—Geirangerfjord and Nærøyfjord; 7—Dorset and East Devon Coast; 8—Primeval Beech Forests of the Carpathians and the Ancient Beech Forest; 9—Stevns Klint; 10—Wadden Sea; 11—High Coast/Kvarken Archipelago

identification of sites at risk, may in some cases not be fully representative of the situation within the site itself if composed of several parts and spatially distributed on the territory.

It is worth mentioning that the UNESCO Risk Index (URI) describes the risk for the preservation of a site, not accounting for risk to people and society in general. This also explains why the UNESCO Risk Index is relatively low for natural sites. In fact, even if the sites can be damaged by natural hazards, modifying the current landscape, these sites do not lose their heritage value. In most cases, the valuable landscape of natural sites is just due to the presence of hazardous geomorphological processes, such as volcanic activity for Etna and Aeolian sites or landslides for the Dolomites. This considering that almost all natural sites do not present forms of anthropisation, except for four cases out of twenty-eight, such as Mt. San Giorgio, Skocjan Caves, Isole Eolie (Aeolian Islands) and Mt. Etna.

The methodology adopted to assess the potential damage scores is intrinsically subjective and reflects the expert belief. However, the procedure for collecting the expert knowledge is explicit and transparent, thus making possible to critically evaluate the outcomes based on the information provided with the analysis. While we think that the increasing availability of data and models will allow to move toward more objective statistical or physically-based models, we believe that the results of the presented research are extremely valuable for the purposes of continental-scale risk management since it offers a homogeneous overview of the hazard combined with a consistent assessment of potential damage and risk.

In view of developing a more quantitative analysis of risk associated with each WHS, this study highlights which are the missing data. In particular, we suggest the collection of information concerning the frequency and magnitude of hazardous events in order to quantify hazard; the technical characteristics of properties (e.g. type of structure, building, foundation, existing damages and weakness), or evidence of ongoing instability leading to enhanced vulnerability condition; the precise distribution or position of single elements at risk within the properties, especially for large WHS such as built areas and cultural routes; the presence of risk mitigation features (e.g. levees, retrofitting); spatial and temporal statistics on residents and visitors; the economic and cultural value of the WHSs and their parts. Finally, the reports could list the mitigation structures and actions which could be implemented at the sites with the relative cost for a classification in terms of feasibility and cost–benefit analysis.

5 Conclusions

The assessment of the risk inside the WHSs is an important task for the preservation of cultural and natural heritage.

The presented methodology is able to exploit available data for a qualitative risk analysis. This methodology can be integrated as new data sets will become available arriving to a quantitative risk analysis. The presence of homogeneously distributed data in Europe, such as those considering subsidence, flood, tsunami and storm events, can allow a more complete definition of the ranking for the prioritisation of the intervention for securing sites. Moreover, the analysis of InSAR data may represent a next step for the implementation of the methodology in order to characterise landslide and subsidence risks.

The research presented in this contribution allowed to identify the most at-risk sites in Europe with also a differentiation of the hazard inside each WHL UNESCO site property. This could be helpful for the planning of future interventions focused on single properties affected by specific hazards.

In addition, this research supports UNESCO to reach some of its objective. In particular, it could help to encourage international co-operation in the conservation and protection of World Heritage Sites affected by a high risk, and to ensure the protection of WHSs at European scale, also improving the data collection for each site. UNESCO could also provide emergency assistance for heritage sites in immediate danger, through technical support and professional training. Finally, the research helps UNESCO to support state parties' public awareness-building activities, clearly showing the level of risk that may affect the existence of the WHSs in comparison with other countries.

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Compliance with ethical standards

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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