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ART-RISK 3.0 a fuzzy—based platform that combine GIS and expert assessments for conservation strategies in cultural heritage

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ABSTRACT

Heritage preservation poses numerous difficulties, especially in emergency situations or during budget cuts. In these contexts, having tools that facilitate efficient and rapid management of hazards-vulnerabilities is a priority for the preventive conservation and triage of cultural assets.

This paper presents the first (to the authors' knowledge) free and public availability Artificial Intelligence platform designed for conservation strategies in cultural heritage. Art-Risk 3.0 is a platform designed as a fuzzy-logic inference system that combines information from geographical information system maps with expert assessments, in order to identify the contextual threat level and the degree of vulnerability that heritage buildings present. Thanks to the possibilities that the geographic information system offers, 12 Spanish churches (11th - 16th centuries) were analyzed. The artificial intelligence platform developed makes it possible to analyze the index of hazard, vulnerability and functionality, classify buildings according to the risk in order to do a sustainable use of budgets through the rational management of preventive conservation.

The data stored in the system allows identify the danger due to geotechnics, precipitation, torrential downpour, thermal oscillation, frost, earthquake and flooding. Through the use of fuzzy logic, the tool interrelates environmental conditions with 14 other variables related to structural risks and the vulnerability of buildings, which are evaluated through bibliographic search and review of photographic images.

The geographic information system has identified torrential rains and thermal oscillations as the environmental threats that mostly impact heritage buildings in Spain.

The results obtained highlight the Church of *Santiago de Jesús* as the most vulnerable building due to a lack of preventive conservation programs. These results, consistent with the inclusion of this monument on the list of heritage at risk defined by Hispania Nostra, corroborate the functionality of the model.

1. Research aim and introduction

The aim of this research is developing and validating a new model for risk assessment that include geographical information system (GIS) hazard maps in a Artificial Intelligence (AI) development to evaluate vulnerability, risk and life… The tool is called ART-RISK 3.0, a free software for risk analysis in the conservation of heritage that could be employed in tablets, cellulars and computers… This tool allows classifying the monuments according to threats and vulnerability.

In order to reach this goal, an artificial intelligence platform designed as a fuzzy-logic inference system has been created to identify the contextual threat level and the degree of vulnerability of monuments, prioritizing the preventive conservation and triage of cultural assets. The input variables of this fuzzy-logic inference system have a hybrid nature since they take values from both GIS maps and expert assessments.Main threats in Spain, for Cultural

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Heritage, have been highlighted such as stress, torrential rains and thermal oscillation in different scenarios studied. Moreover, the use of this tool allows also preparing emergency response in cities or regions in function of the main risks.

The model is designed to identify heritage in risk, the case of study in Spain validate the results, and is in concordance with the list of heritage at risk defined by Hispania Nostra [1].

The degradation of Heritage is influenced by many anthropic and environmental factors. The geotechnics of the land [2]; environmental factors [3–11] and emergency events such as earthquakes [12–14] and floods [15–18] are threats that generate complex degradation processes and hinder the conservation of buildings [6,8,12,13,16,18–22].

Analysing the dangers of the environment through the use of Geographic Information Systems (GIS) allows registering the hazards present and identifying contexts of risk. The first studies in this line of research date from 1990 [23–25] and currently there are numerous projects focused on the use of GIS for the management of heritage structures, [26–34], the analysis of vulnerability [35–37], natural hazards [20,22,29,35,38–41] and anthropic hazards [42–45].

However, studies that jointly assess all short-term threats and combine them with vulnerability still require in-depth research.

The development of Infrastructures for Spatial Information (IDE) and viewers facilitate access by specialists to geospatial data. Despite of this, its use as a source of information in heritage interventions is still scarce.

In this context, the technique of artificial intelligence known as fuzzy logic is an effective method that allows to model uncertainties and ambiguities in a similar way to human reasoning system. Thus, the combination of fuzzy logic and GIS provides a suitable tool to handle uncertainty and make decisions in solving problems [46,47]. In recent years, its application for heritage buildings has yielded promising results [48–52].

Developing tools based on the use of AI and GIS facilitates the arrival of geospatial information to a much broader community of professionals not specialized in working with GIS. This is the foundation of the methodological model developed for the free artificial intelligence platform Art-Risk3.0. (https://www.upo.es/investiga/art-risk-service/art-risk3/) [53].

Art-Risk3.0 compiles standardized information on the different variables that influence heritage degradation processes. It analyses the threats to which buildings are subjected to and their vulnerability to these threats. The GIS project that serves as the basis for Art-Risk3.0 includes different georeferenced thematic layers of environmental hazards existing throughout the Spanish context. The proposed fuzzy—based tool makes use of two types of input variables that are interrelated through the inference rules. On one hand, aspects as architectural uniqueness, material composition, maintenance policies and the state of conservation give rise to 14 variables that are evaluated during expert inspections or through bibliographic search and review of photographic images. On the other hand, the information stored in the GIS allows us to work with other 7 variables, whose crisp or numerical nature becomes fuzzy by the fuzzification module. Thanks to the use of GIS and AI, it has been possible to develop a predictive model that assesses risk as a function of both vulnerability and hazards, and the functional life of a building as one inverse to its risk. The result is a computer application capable of obtaining the hazard, vulnerability and functionality index of heritage assets analysed based on their geographic location and the inspections carried out.

This work describes the GIS on which Art-Risk3.0 is based on and evaluates its usability. The results allow the identification of existing environmental hazards in Spain and comparatively analysing the level of risk, as has been demonstrated through the case study of 12 buildings of heritage interest. The classification of the buildings analysed according to their indexes of vulnerability, hazard and functionality support decision making for their preventive conservation.

2. Material and methods

2.1. Case studies

The study area covers the entire Spanish territory. To cover the whole map of environmental hazards, 12 churches distributed over the country's geography were chosen. Fig. 1 shows the buildings analysed and their location.

All churches have their origins between the 11th to 16th centuries, they present construction remodeling from different periods, and are representative examples of Romanesque, Gothic, Mudejar and Baroque styles. Due to their high cultural value, they are all protected under the legal status of Asset of Cultural Interest (BIC). Their construction characteristics are similar because they are religious building but their state of conservation, and environmental context differ in order to analyze the variability and capacity of the model.

2.2. Methodology

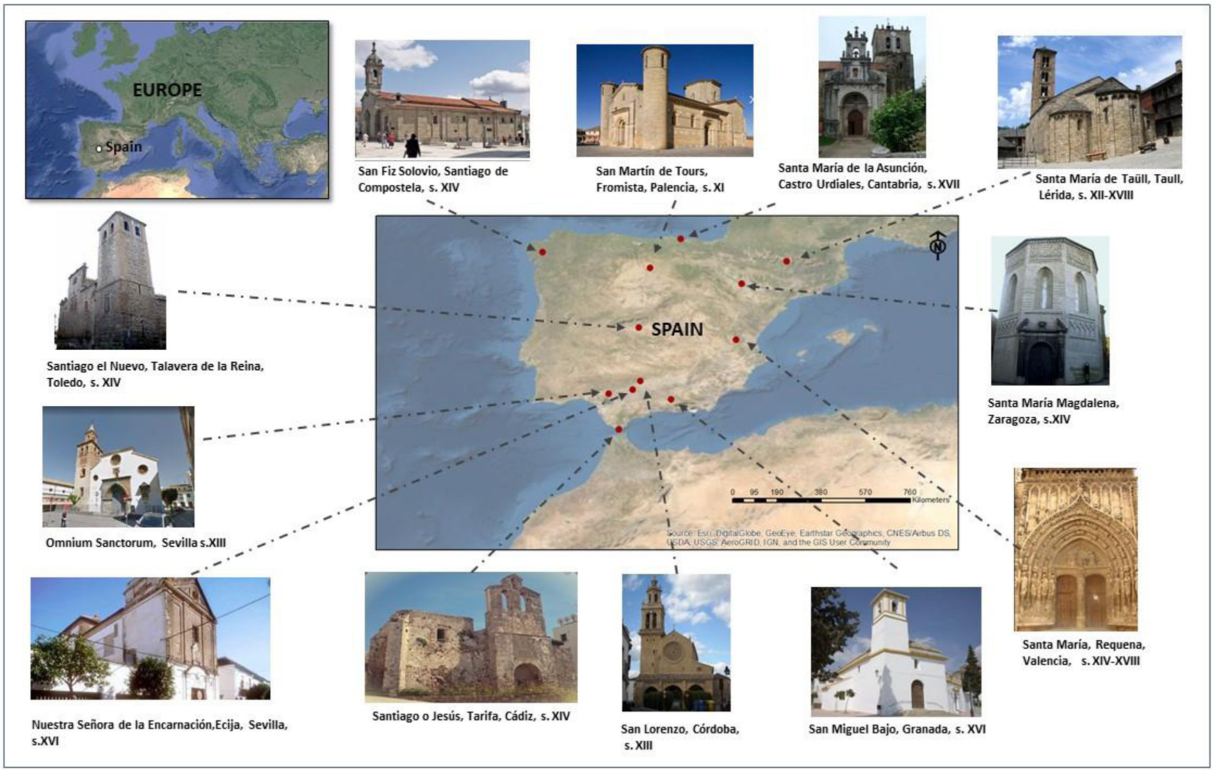
During the hazard and vulnerability study of the monuments, the Art-Risk analysis model described in previous works by the authors has been used [51]. A useful fuzzy inference system has been developed previously by the authors [54,51], which is able to manage the uncertainty associated with the degradation of heritage buildings. It carries out an integrative analysis of heritage constructions, considering vulnerabilities and hazard factors. In this work, this fuzzy—based platform is improved by linking it to GIS. The result is Art-Risk3.0.

2.2.1. System architecture

Art-Risk3.0 [53] is a web tool designed not only for working with computers (PCs, laptops) but also for working with mobile devices (tablets mobile phones). All the technology used in its implementation is based on Open-Source code. Art-Risk3.0 architecture is composed of three main parts or modules: an interface, a GIS database and an artificial intelligence engine.

The interface uses standard web technology and is responsive. The GIS database uses GRASS software [55] and contains the hazard maps that allow the generation of automatic variable values. The values of these variables are obtained directly from the maps contained in the GIS database from the coordinates of a building. The artificial intelligence—based platform developed was implemented in the Xfuzzy open-access software program, which can be executed on platforms using Java Runtime Environment—JRE. The Xfuzzy system integrates a set of user-friendly tools to cover the different stages involved in the design process based on fuzzy logic, from the initial description to the final implementation [56]. Fig. 2 shows the workflow scheme of the Art-Risk3.0 tool.

In a regular workflow the user must enter the geographical coordinates of the building (WGS84 format) he/she wants to evaluate. For this purpose, a graphic map viewer based on OpenStreetMap is available. This allows to obtain the latitude and longitude of the building. It is also possible to enter the coordinates directly. This also guarantees the accessibility of Art-Risk3.0 (see Section 2.2.3). The geographical coordinates are used to index a series of maps in the GIS database and obtain the values of the input automatic variables. Then, the user has to enter the values of the other variables manually. For this purpose the tool provides a complete user manual and an on-line help system to help determine the most appropriate input variable values. Once the 21 input variables have



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Fig. 1. Churches analysed: Santiago o Jesús, San Miguel Bajo, Omnium Sanctorum, Nuestra Señora de la Encarnación, San Lorenzo Martir, Santiago el Nuevo, San Martín de Tours, Santa María, Santa María de La Asunción, Santa María Magdalena, San Fiz Solovio, Santa María de Taüll.

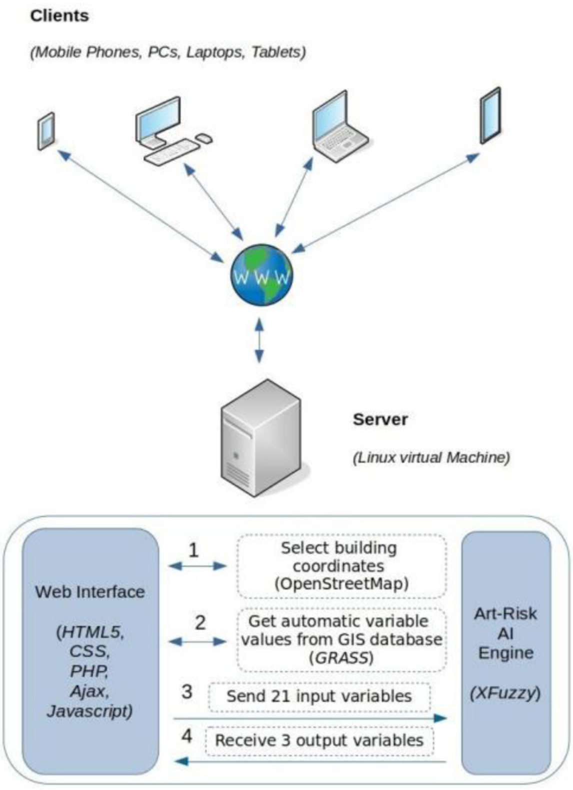


Fig. 2. Art-Risk3.0 platform work flow.

been established, the user requests the tool for the result, which is returned by means of three output variables. These variables indicate the vulnerability, the hazard and the functionality index of the building. The description of all the variables and the interpretation of the results are specified in the manual for users [57].

2.2.2. Geographic information systems

For the processing of cartographic data, GRASS®7.6 has been used, a free and open source GIS used for the analysis of geospatial data. The data has been stored according to a geodetic system of WGS84 geographic coordinates.

There are 7 hazard variables mapped in the GIS: geotechnics (Ar1), average precipitation (Ar16), rain erosion (Ar17), thermal stress (Ar18), frost (Ar19), earthquakes (Ar20) and floods (Ar21). The presence and intensity of these variables are available for the entire Spanish territory.

The geotechnical map (Ar1) shows construction hazards. The values were obtained from the General Geotechnical Map at a scale of 1: 200,000 created by the Geological and Mining Institute of Spain [58]. The criteria followed by IGME were lithological, geomorphological, hydrological and geotechnical (load capacity, settlement and various geotechnical). According to these criteria, the map indicates an index that quantifies the constructive capacities of the land according to a scale of 1–5 (1-very favourable, 5-very unfavorable). This resource is available online in the form of 93 downloadable sheets in jpg format.

The average precipitation map (Ar16) shows the hazard according to the amount of annual rainfall per unit area (mm/m2). The values were obtained from the Iberian Climate Atlas developed by the Spanish Meteorological Agency [59] and present an average based on annual rainfall for a period of 30 years (1971–2000). The period of time analysed corresponds to the Climatological Standard

Normals, reference values established by the World Meteorological Organization (OMM). The cartographic coverage has been obtained by interpolating the discrete data from the Spanish Meteorological State Agency (AEMET) meteorological stations. The method employed was kriging and it used altitude, distance to the coast and latitude-longitude as external variables. The data obtained by AEMET are raster files with a spatial resolution of 250 × 250 m and an ETRS89 projection system. This resource is available online as a jpg file (AEMT, 2011).

The rain erosion map (Ar17) shows the hazard associated to the rain intensity. The values have been obtained according to the torrential rainfall index of the Highways Standard Instruction 5.2–1C: Surface Drainage published by the Spanish Ministry of Public Works and Urbanism [60]. The torrential rain index indicates the relationship between hourly precipitation and the corrected daily average. This resource is available online as an isobar map in jpg format.

The thermal stress map (Ar18) shows the mean value of the difference between the recorded annual maximum and minimum temperatures. This isobar map comes from the daily thermal oscillation maps drawn up by the National Geographic Institute of Spain (IGN) for the National Atlas [61]. Discrete data comes from AEMET.

The frost map (Ar19) shows the danger associated with air temperatures below 0 °C. The values have been obtained from the Risk Map: frosts and cold hours in mainland (2002–2012) [62], and they map the number of days of annual frost according to the average minimum temperatures from 2002 to 2012. This cartography is part of the results of the LIFE sigAGROasesor project, which seeks to develop a Web Platform to help decision-making in the agricultural sector. The maps generated by AEMET are based on an interpolation of data from state thermometric stations. The method employed was kriging and it used altitude and distance to the coast as external variables. The results obtained are raster files with a spatial resolution of 500 × 500 m. This resource is available online as a jpg file (AEMT, 2015).

The seismicity map (Ar20) shows the hazard associated with the occurrence of earthquakes. The values come from the Standard for Earthquake Resistant Construction: General and Buildings Section: NCSE-02 of the Spanish Ministry of Development [63] and show the basic seismic acceleration (characteristic value of the horizontal acceleration of a terrain surface), expressed according to gravity. The minimum value is of 0.04 g and the maximum is of 0.16 g. The cartography available online for your reference includes a jpg file [63].

The flood map (Ar21) shows the areas susceptible to a river or sea flood according to return periods of 10, 50, 100 and 500 years. The data has been obtained from the National Flood Zone Cartography System (SNCZI), developed by the Spanish Ministry of the Environment and Rural and Marine Affairs according to Directive 2007/60 on the evaluation and management of flood risks [64,65]. Currently the information is available in the SNCZI viewer [66] and the visualization service catalog INSPIRE for water [67]. To identify flood zones, we have worked with the Web Map Service (WMS) available starting from the 1:1000,000 scale.

For its use in GIS, all this cartographic information has been digitized, reclassified and converted into vector files. The different measurement scales (temperature, precipitation, seismicity of the land …) have been homogenized to consider these together. The method used was a reclassification according to a common scale of intensity of hazards 1–5 (1. Very low; 2. Low; 3. Medium; 4. High; 5. Very high) according to the works previously developed by Ortiz et al. [68]. Table 1 shows the equivalences established between the different scales.

Once digitized and reclassified, a series of vector polygons was obtained from each of the variables that represent the quantitative variation of the phenomenon in space. The qualitative information has been stored in tables associated with these polygons.

The 12 churches analyzed have been georeferenced in a vector file. Overlaying this file over the different hazard maps allows us to know the intensity with which environmental threats affect buildings.

It is currently possible to work online with the cartography described by using the platform Art-Risk3.0. By entering the geographic coordinates of the building to be analyzed, the tool retrieves the alphanumeric information contained in the GIS layers and produces an automated list of hazard values for each geographic point entered.

In the case studies featured, this tool has been used to carry out a comprehensive analysis of the levels of hazard, vulnerability and functionality of 12 temples. The use of the app has enabled the addition of the environmental hazard variables stored in the GIS, 14 more variables of vulnerability and structural hazards that are analyzed by inspection: Built environment (Ar2), Constructive system (Ar3), Population growth (Ar4), Heritage value (Ar5), Value of movable assets (Ar6), Occupancy (Ar7), Maintenance (Ar8), Roof design (Ar9), Conservation (Ar10), Ventilation (Ar11), Facilities (Ar12), Fire risk (Ar13), Overloads (Ar14), Structural modifications (Ar15). These variables have been obtained through bibliographic search and review of photographic images (Table 2).

As a result, the 12 buildings analyzed have been classified into groups according to the indices produced by the Art-Risk3.0. This makes it possible to compare the results obtained together and identify the buildings with the highest risk of loss.

2.2.3. Accesibility

Accessibility is an important part of any good design of a computer tool. Not only is it required by many legal regulations but it also contributes to a better dissemination of results. In Art-Risk3.0 a study of web accessibility has been carried out using automatic verification tools as support and help. There are many tools to help automatically verify the accessibility of a website. However, many of these tools are not updated or currently maintained.

In particular, Tingtum Checker [69] and WAVE [70] have been used. The first tool was developed through the European Horizon 2020 program which funds research and innovation projects in various thematic areas. Tingtum Checker is intended to conform to the Web Content Accessibility Guidelines 2.1 (WCAG2.1) of the W3C Web Accessibility Initiative (WAI). WAVE was launched in 2001 at the University of Utah (USA). It provides fairly clear, usable and easy to interpret reports. WAVE also conforms to WCAG2.1 guidelines.

Thanks to these tools and manual checks, Art-Risk3.0 site conforms to WAI WCAG 2.1 at AA Level. However, this is not entirely true as there is an exception. The contact form has a simple captcha that is not fully accessible. All captchas have usability issues and many have significant accessibility barriers. However, the use of captchas is a restriction commonly imposed on many web hosts for security reasons [71].

2.3.4. Usability

A good usability is a key factor for the success of any computer system. To verify the correct usability of Art-Risk3.0, the ISO 9241–11 [72] standard has been followed. This standard takes into account the ergonomics and usability of terminals with display screens. ISO 9241–11 framework makes it possible to visualize all the factors that can affect the usability of a system in use, from a real perspective, which is fundamental in determining the real user needs [73,74].

Specifically, the ISO 9241–11 standard proposes the evaluation of usability through three factors: effectiveness (accuracy and completeness with which users achieve specific goals), efficiency, (re-

Table 1
Equivalences between the different scales.

Variable	Original Scale	Hazard Scale
Ar1. Geotechnics	Optimum ground conditions in terms of stability	(1) Very low hazard
	Favourable ground conditions in terms of stability	(2) Low hazard
	Acceptable ground conditions in terms of stability	(3) Medium hazard
	unfavorable ground conditions in terms of stability	(4) High hazard
	Very unfavorable ground conditions in terms of stability	(5) Very high hazard
Ar16. Average rainfall	<600 mm/m2	(1) Very low hazard
	600–750 mm/m2	(2) Low hazard
	750–1000 mm/m2	(3) Medium hazard
	1000–1200 mm/m2	(4) High hazard
	>1200 mm/m2	(5) Very high hazard
Ar17.Raindrop impact	IT<7	(1) Very low hazard
	IT 7–8	(2) Low hazard
	IT 8–9	(3) Medium hazard
	IT 9–10	(4) High hazard
	IT<10	(5) Very high hazard
Ar18. Thermal amplitude	<6 °C	(1) Very low hazard
	6–7 °C	(2) Low hazard
	7–8 °C	(3) Medium hazard
	8–10 °C	(4) High hazard
	10–12 °C	(5) Very high hazard
Ar19. Frozen damage	<10 days	(1) Very low hazard
	10–20 days	(2) Low hazard
	20–80 days	(3) Medium hazard
	80–125 days	(4) High hazard
	>125 days	(5) Very high hazard
Ar20. Seismic hazard	0,04 g	(1) Very low hazard
	0,04–0,08 g	(2) Low hazard
	0,08–0,12 g	(3) Medium hazard
	0,12–0,16 g	(4) High hazard
	>0,16 g	(5) Very high hazard
Ar21. Flooding	No floodable area	(1) Very low hazard
	Return period 500 years	(2) Low hazard
	Return period 100 years	(3) Medium hazard
	Return period 50 years	(4) High hazard
	Return period 10 years	(5) Very high hazard

sources expended in relation to the accuracy and completeness with which users achieve goals) and satisfaction (comfort and acceptability of use).

The usability of Art-Risk3.0 was evaluated according to the ISO 9241–11 standard by means of a task carried out on 10 users. These users were specialists in areas related to historical and cultural heritage. None of the users had previously used the tool. The task consisted in evaluating the church of Santa Marina in Seville using PCs or laptops. All users were provided with the values of the 21 system input variables (both automatic and manual) and the 3 output results (vulnerability, hazard and functionality index) by means of a spreadsheet. Users had to use the Art-Risk3.0 tool to obtain these output results from the values of the input variables. This implied:

1) Obtain the coordinates of the church on the *Art-Risk3.0* online map and validate them to obtain the results of the 7 automatic input variables.
2) Entering manually in the tool the values of the remaining 14 manual variables.
3) Ask the system to return the 3 output results.

In order to evaluate the effectiveness, it was checked whether the task could be completed or not. That is, they checked that the output results obtained with the Art-Risk3.0 tool coincided with those provided by the spreadsheet. All of them finished the task correctly. Therefore, 100% efficiency was obtained.

For the efficiency evaluation the time spent on evaluating the church with the tool was measured. The average time used was 5 min and 26 s. However, the standard deviation was 3 min and 50 s. This value, proportionally so high, is due to the fact that a user spent 15 min to complete the task. However, all other users took a maximum of 8 min. If this extreme case is ruled out, the resulting average is 4 min and 22 s with a standard deviation of 2 min and 14 s.

The evaluation of satisfaction was carried out using the standardised SUS (System Usability Scale) tool. It consists of a 10 items questionnaire with five response options for respondents. SUS proved to be an extremely simple and reliable tool for use when doing usability evaluations [75]. The average value obtained was 92 points out of a total of 100 points (where 100 indicates the highest possible level of satisfaction). The standard deviation was 9.6 points.

As a final conclusion of the tests carried out, it can be stated that the Art-Risk3.0 tool presents a fairly satisfactory level of usability.

3. Results

3.1. Assessment of environmental threats in heritage buildings as a basis for preventive conservation

Fig. 3 shows the national distribution of geotechnical hazards. 33% of the Spanish territory presents a high or very high threat related to the subsoil and its geotechnics [58]. Santiago de Jesus, Santa Maria de Taull and Nuestra Senora de la Encarnacion are the 3 churches analysed located in highly dangerous environments. In these contexts, erosion phenomena and landslides can generate problems in the foundations of structures [2]. For this reason, the presence of cracks and fractures must be monitored.

As shows Fig. 4, the highly dangerous contexts due to rainfall are centered to the north. They occupy 11% of the national territory and are mainly associated with mountainous areas with

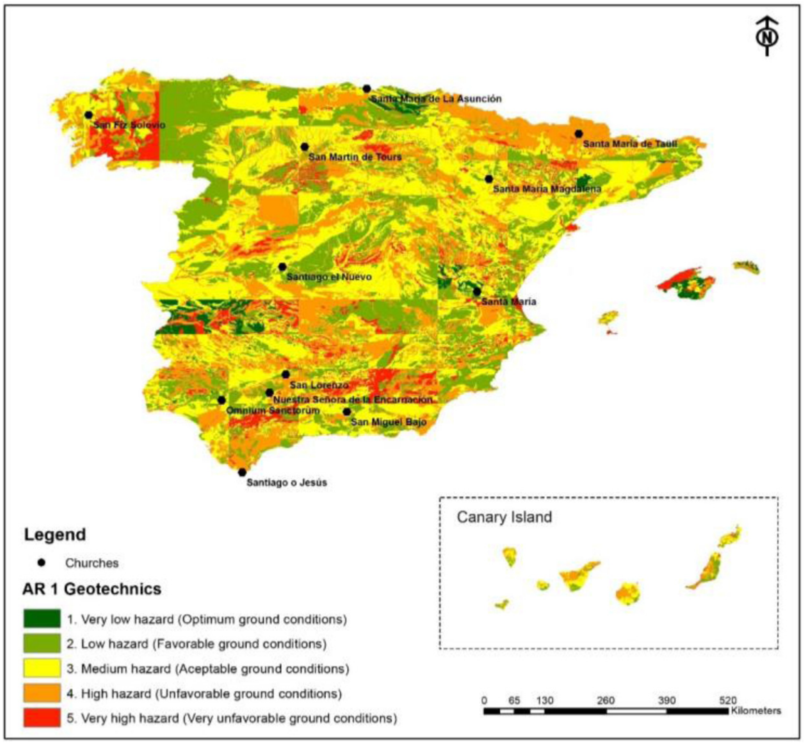


Fig. 3. Map of geotechnics carried out by GIS and churches studied.

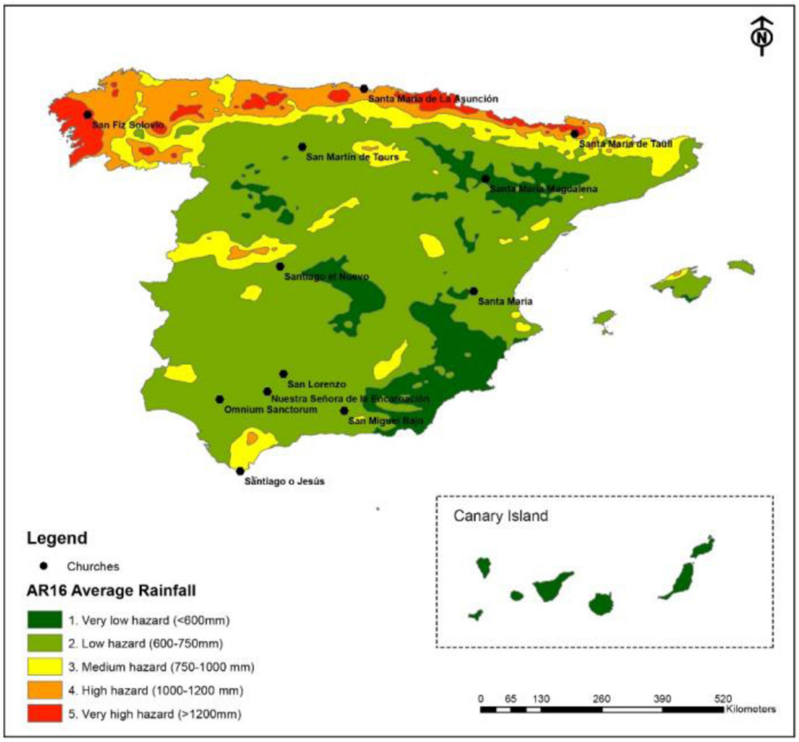


Fig. 4. Map of average rainfall carried out by GIS and churches studied.

annual averages of more than 1000 mm/m2. Only the *San Fiz de Solovio* Church is exposed to high danger due to rainfall. Although to a lesser extent, *Santa Maria de Taull* and *Santa Maria de la Asuncion* are also located in dangerous sites due to rain (Fig. 4). Rain favours the physical-chemical degradation of buildings and biological colonization. The processes of dissolution and migration of salts are problematic in these environments, especially combined with thermal oscillations. Although it is necessary to know the mineralogical characteristics and the porosity of the materials used in the buildings in greater detail [76–78], the clays contained in the sandstone of the *Santa María de la Asunción* church portal are especially vulnerable to environments such

Table 2
variables of vulnerability and structural hazards of the 12 churches analyzed.

	Omnium Sanctorum	Santa María Magdalena	Santiago el Nuevo	Santa María	Santiago o Jesús	San Fiz Solovio	Santa María de Taüll	San Martín de Tours	Santa María de La Asunción	San Lorenzo Martir	Nuestra Señora de la Encarnación	Miguel Bajo
Ar2. Built environment	2	1	1	3	3	1	1	1	1	1	3	3
Ar3. Constructive system	3	2	1	1	2	2	1	2	4	2	2	2
Ar4. Population growth	3	2	2	3	3	2	2	3	2	3	3	2
Ar5. Heritage value	1	1	1	1	1	1	1	1	1	1	2	1
Ar6. Value of movable assets	2	2	2	3	5	3	5	4	2	2	3	1
Ar7. Ocupancy	3	3	3	3	5	2	4	3	3	3	4	3
Ar8. Maintenance	3	3	3	2	5	2	2	2	2	2	3	3
Ar9. Roof design	2	3	2	2	2	2	2	2	3	3	2	3
Ar10. Conservation	3	1	1	2	5	2	2	1	3	2	2	2
Ar11. Ventilation	2	2	2	2	1	2	1	2	2	2	2	2
Ar12. Facilities	1	1	1	1	5	1	1	1	1	1	1	1
Ar13. Fire risk	2	2	2	1	1	2	1	1	2	2	2	2
Ar14.Overload	2	2	2	2	1	2	2	2	2	2	2	2
Ar15. Structural modifications	1	3	1	1	1	1	1	1	2	2	2	2

as the one just described [21]. The presence of moisture stains and biopatines are indicators of the most problematic locations and must be monitored to ensure the maintenance of buildings [79–82].

Although the annual rainfall averages are not high in a large part of the country, approximately 77% of the territory has a torrential index higher than 9 (high or very high danger). In turn, 6 of the analysed churches have environments of high danger due to torrential rains and only 1 of them is located in a place of low danger (Fig. 5). The Mediterranean area and the northwestern Europe will be strongly affected by the effects of climate change [3]. In Spain, it is estimated a reduction in total precipitation values and an increase in torrential rains [1] that indicates a growth in the level of risk associated with extreme weather events and raindrop impact. Overloads on roofs, gutters and downspouts are problems that affect vernacular architecture and buildings in poor condition in these environments. Floods and landslides associated with storms can compromise the stability of the building [21]. Monitoring before and after strong storms is essential for their preservation.

Fig. 6 shows the danger due to heat stress. More than 86% of the national territory presents oscillations of more than 10 °C. The areas far from the coast are the ones that pose the greatest problems. In the near future, due to climate change, in Spain is predicted an increase in temperature, day-night fluctuations [6] particularly in the cities. This situation will increase thermal hazards, especially in the south of Spain. Of the case studies analysed, 9 are affected by contexts of high thermal danger. In response to thermal cycles, stone buildings undergo dimensional changes that cause mechanical damage. Microcracks may appear in granite [83], and in slightly porous materials, such as marble, cracks, fractures and increased porosity can also appear [81].

The danger associated with temperatures equal to or lower than 0 °C is outlined in Fig. 7. Approximately 21% of the Spanish territory shows averages with more than 80 days per year of frost hazard, and two of the analysed temples are located in these highly dangerous environments. Freezing and thawing cycles are one of the main degradation factors of stone buildings, with the magnitude of the damage being greater in materials with a porosity greater than 5% [21]. The temperature differences between the innermost layers and the outer layers of a wall can generate strong stresses during thawing [10,81] and must be monitored. Although they are not frequent in Spain, storms like Filomena, together with low temperatures, can generate additional problems due to the weight of snow on the roofs or due to falling branches and trees. Irregularities in the rainfall regime and/or intense snow storms are phenomena derived from climate change [84]. On the Mediterranean coast, the probability of extreme events is increasing [85] and the adaptation of heritage buildings is essential to minimize risks [86,87].

As seen in Fig. 8, Spain is not a particularly seismic country, however 5% of the national territory has an earthquake severity index higher than 0.12 g. The most problematic locations are in the southeast of the peninsula. Out of the case studies analysed, the *Church of San Miguel Bajo* is located in a highly dangerous context due to seismic hazard. This type of environment can cause serious damage to the people who inhabit these spaces and structural deterioration that could imply the total loss of the building. Although there are numerous studies regarding seismic monitoring in heritage contexts [13,88–90], it is essential to develop emergency plans and regular drills as part of the building management for that location. Likewise, the periodic use of Art-Risk3.0 before and after an earthquake allows prioritizing emergency interventions and minimizing the risk of loss after an emergency situation.

Regarding flood zones, those with a return period of less than 50 years have been considered a high threat (Fig. 9). They are

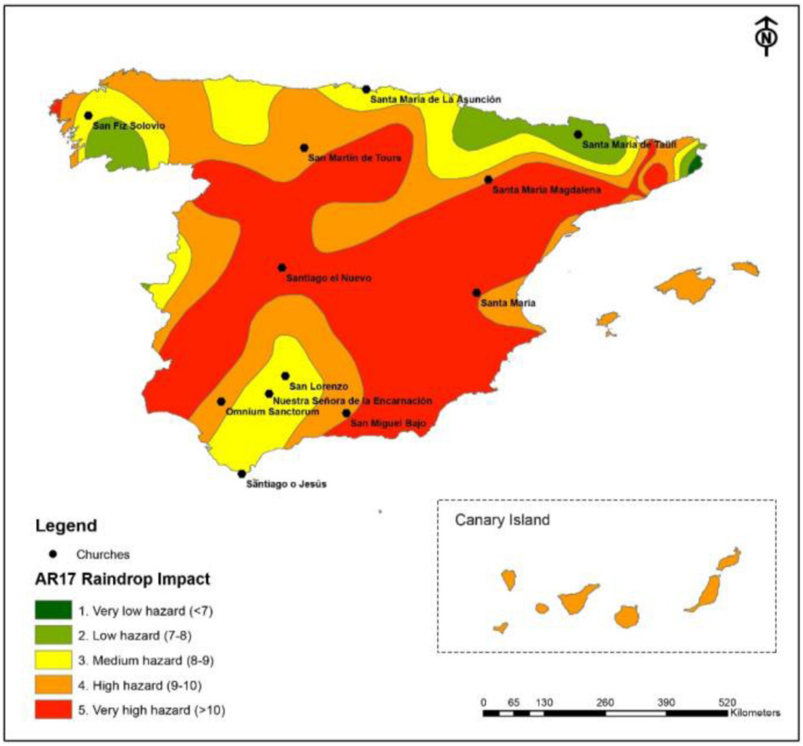


Fig. 5. Map of raindrop impact carried out by GIS and churches studied.

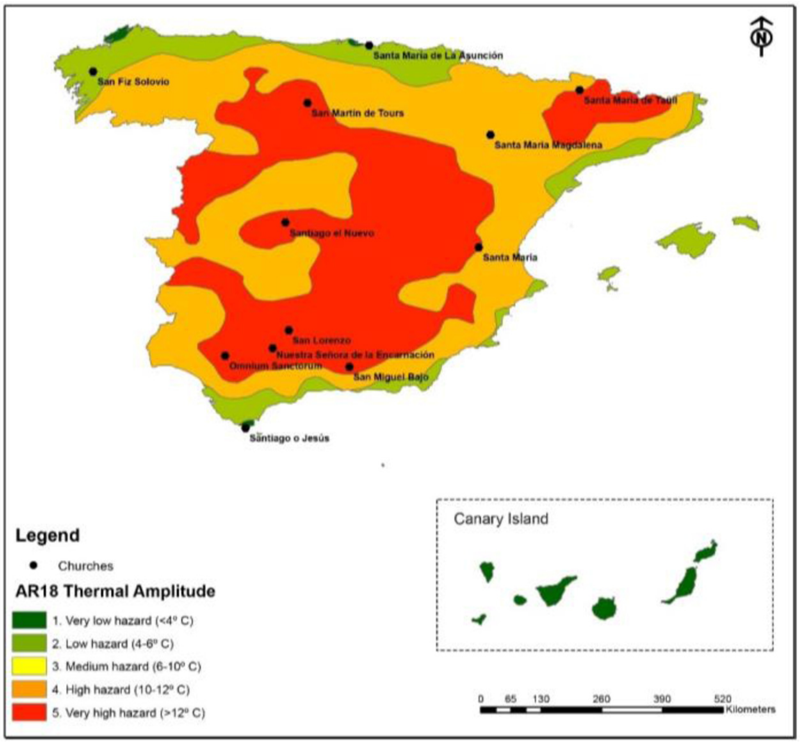


Fig. 6. Map of thermal amplitude and churches studied.

mainly regions near major river beds and their discharge outfalls. 11 of the case studies analysed are located in areas of low or very low danger, with return periods of 500 years. The development of emergency plans and periodic drills is essential for the sustainable management of the Church of *Santa Maria de la Encarnacion*, a monument located in a high-risk environment due to flooding.

3.2. Evaluation of the index of Hazard, vulnerability and functionality

Art-Risk3.0 allows the evaluation of the Index of Hazard (HI), Vulnerability (IV) and Functionality (IFL) of the 12 buildings analyzed (Table 3). The classification according to the IV and IF offered by the tool allows us to identify which buildings need the most

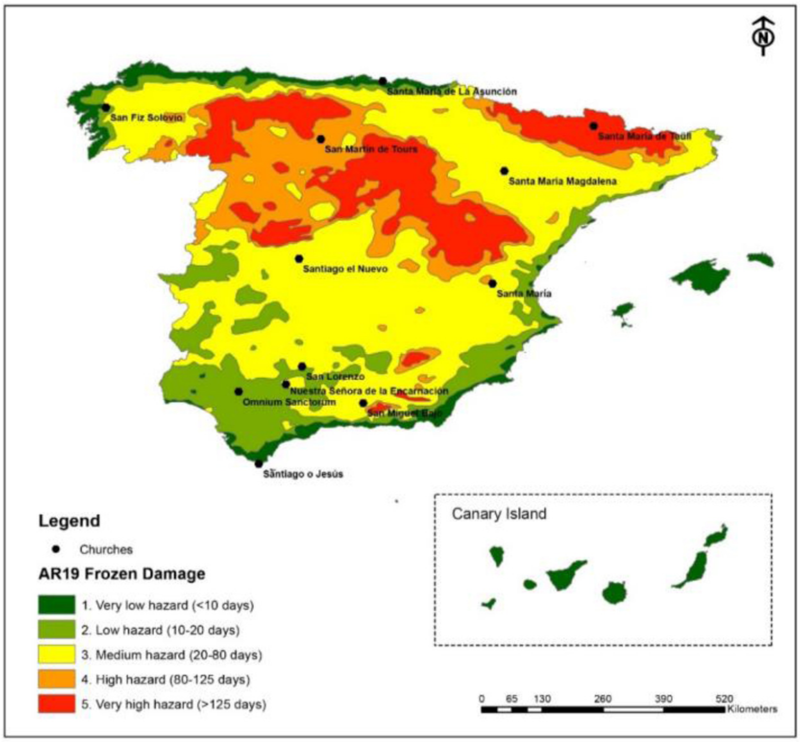


Fig. 7. Map of frozen damage and churches studied.

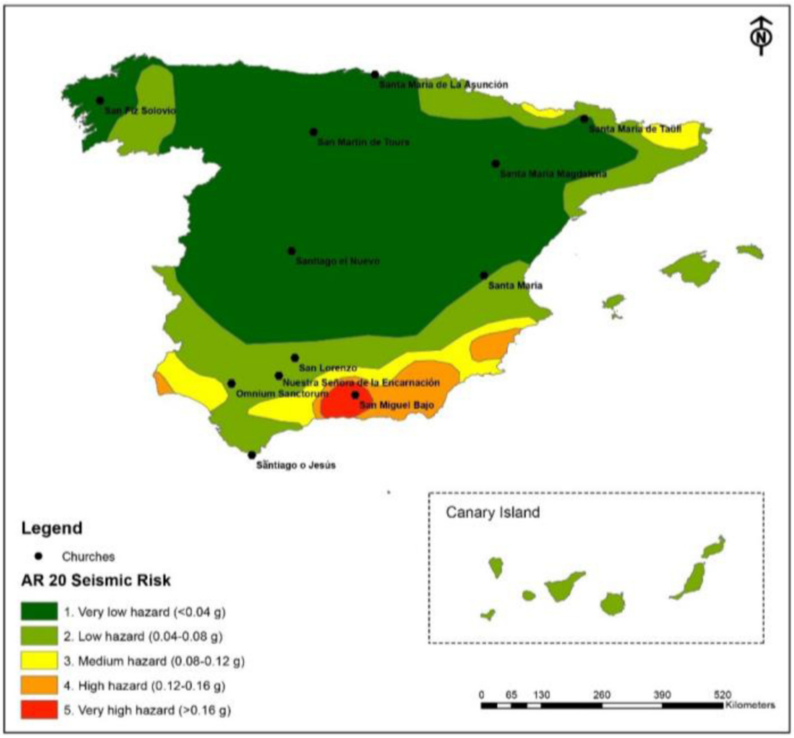


Fig. 8. Map of seismic hazard and churches studied.

urgent intervention. Santiago o Jesús is the building that presents the greatest problems due to its poor state of conservation. San Miguel Bajo, Omnium Sanctorum and Nuestra Señora de la Encarnación also present a greater urgency than the rest of the buildings analyzed.

The results registered (Fig. 10) are interpreted according to the color code provided in the tool manual [57]. The traffic light scale (red-yellow-green) corresponds to the values of vulnerability, hazard and functionality recorded in Table 3. It allows to identify the buildings that present a greater probability of loss due to their low functionality caused by a dangerous environment or by the highest vulnerability of the building.

The VI is the result of the constructive vulnerability (roof design, construction system, geological location, built environment

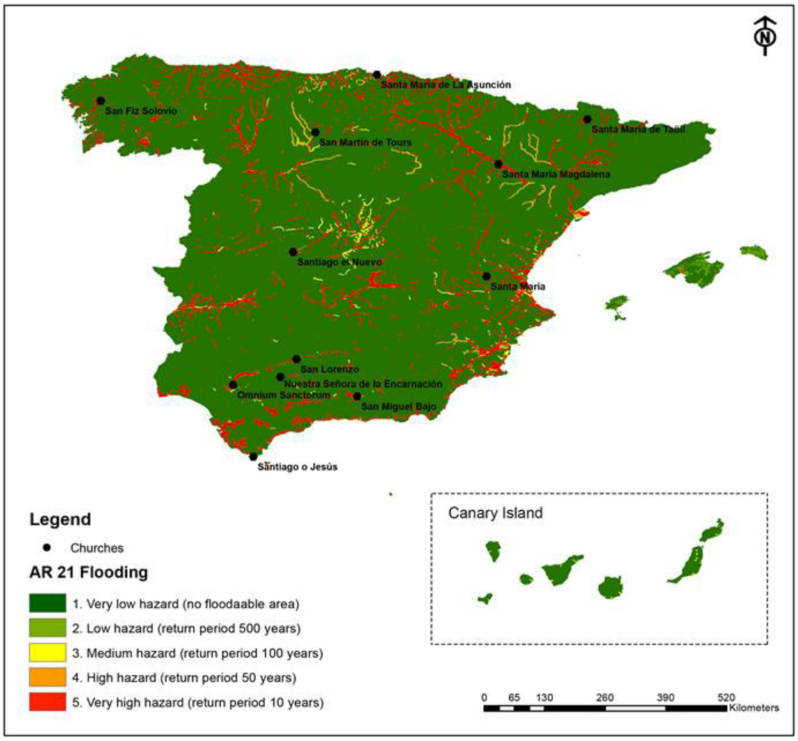


Fig. 9. Map of flooding hazard and churches studied.

Table 3
Index of Hazard, Vulnerability and Functionality.

Church Name	Vulnerability Index (VI)	Hazard Index (HI)	Functionality Index (FLI)
Santiago o Jesús	74	35	50
San Miguel Bajo	54	45	51
Omnium Sanctorum	54	44	51
Nuestra Señora de la Encarnación, Monjas Blancas	52	45	51
San Lorenzo Martir	44	45	56
Santiago el Nuevo	44	43	57
San Martín de Tours	44	43	57
Santa María	37	43	60
Santa María de La Asunción	46	34	60
Santa María Magdalena	44	34	62
San Fiz Solovio	44	34	62
Santa María de Taüll	44	34	62

and conservation), anthropic affections (population growth, occupancy, heritage value and value of movable assets) and maintainability. Fig. 10 shows those buildings that present a greater weakness to face of external threats. Among the buildings analyzed, only the Church of Santiago o Jesús are colored in red because presents an VI higher than 60. This is due to its poor state of conservation, a condition that has, in parallel, led to its inclusion in the heritage building red list [1] https://listarojapatrimonio.org/ The non-existence of maintenance policies and low occupancy due to the state of abandonment of the building also influence the high vulnerability registered. The maintenance and restoration interventions carried out in the rest of the buildings keep them at medium-low levels of vulnerability. Building restoration plays a crucial role in urban regeneration policies. Heritage represents a fundamental resource to generate employment and diversify the economy through sustainable tourism [4,2], particularly in rural areas, which in many case are at risk of being depopulated. This information is recovered by the variables Art 4: Population grown and Art 7: Occupancy in the Art-Risk 3.0 model. Those variables are particularly important in Spain, a country where in 2019 tourism will increase by 154 million euros and 2.68 million jobs (12% of the total employment) which represented 12.7% of gross domestic product (https://www.ine.es/dyngs/INEbase/listaoperaciones.htm). Despite this, especially in growing cities, it is essential to have a planning system that allows minimizing the dangers associated with uncontrolled tourism and gentrification, as well as promoting sustainable use of heritage [5].

The HI captures the results of the joint analysis of environmental hazards (thermal stress, precipitation, frost…) as well as structural hazards (ventilation, fire load, structural modifications…). Fig. 10 shows that five of the case studies analyzed are colored green because they are in contexts of low hazards (HI <40). The remaining seven cases are colored yellow because they are in environments with a RI of 40–60, so they require periodic monitoring or a reduction of the threats increasing their structural resistance. The hazard mapping reviewed in the interior section indicates that the most common hazards that increase this index are raindrop impact and temperature fluctuations. In addition, climate change will increase the danger associated with extreme storm and temperature, so it is essential to define solutions that allow minimizing the risk, for example by ensuring the proper functioning of roofs.

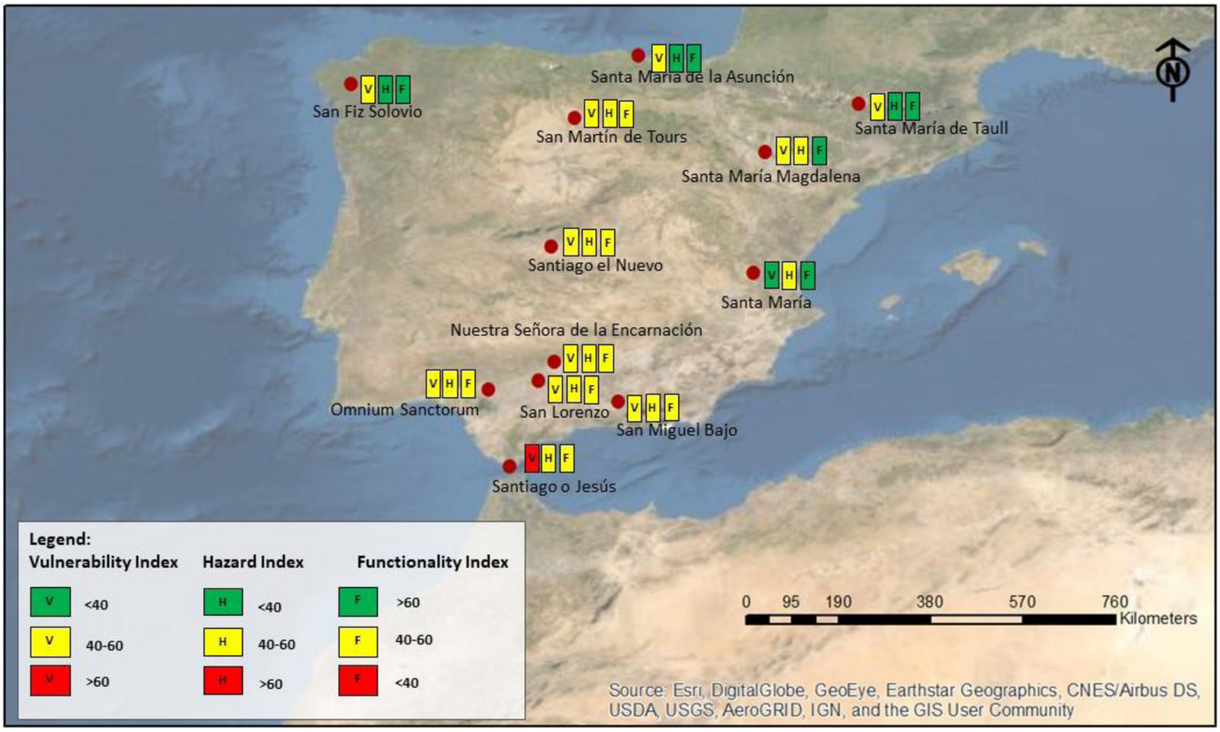


Fig. 10. Index of vulnerability, hazard and functionality (green: optimal conditions, yellow: acceptable conditions, red: unacceptable conditions). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The IFL interrelates the variables of hazard and vulnerability and determine the building useful life. A higher IFL indicates a lower risk of loss. Picture 10 show that 5 of the buildings analyzed are colored in green because they have an IFL greater than 60 and therefore do not pose urgent problems. The recommendation for preventive conservation plans in San Fiz de Solovio, Santa María de la Asunción, Santa María de Taull, Santa María Magdalena y Santa María includes periodic reviews. The other buildings (San Martín de Tours, Santiago el Nuevo, Nuestra Señora de la Encarnación, Omnium Sanctorum, San Lorenzo, San Miguel Bajo and Santiago Jesús), colored in yellow and with an IFL ranging between 40 and 60 must have a deeply diagnosis and a intervention in the short-medium term to ensure their maintenance. In addition, after their intervention, they must include long-term preventive conservation plans [57].

To sum up, the three output indicators (VI, HI and IFL) may be associated with certain failure characteristics (pathologies) in a historic building. Thereby, increasing the life expectancy of the building involve to solvent the failures (pathologies) that increase vulnerability due to structural or environmental hazards. Although the parameter on typical failures of historic buildings is not a variable that is measured directly as an input to this model, it is considered as an indirect variable mainly associated to Conservation (AR10), Overload (Ar14) and Structural modifications (AR15). Moreover, the model is capable of measuring the vulnerability of buildings, regarding the analysis of the roof design, state of conservation, geological situation, maintenance, among other kind of parameters, and measures the effects of external hazards associated with deterioration due to static-structural, atmospheric or anthropogenic risks. When analyzing homogeneous building complexes, under similar environmental conditions, well-defined conclusions can be obtained about the most frequent failure characteristics that generate increases or decreases in the model's output indicators. This type of analysis has already been carried out by the research group in other publications ([91] and [54,92]), which yielded very interesting conclusions after analyzing a set of 400 historical records between the XIV and XXI centuries in a set of 20 Mudejar churches located in the south of Spain and the same building after the restoration of its pathologies.

Today, citizen science offers an interesting way to updating data thanks to the public collaboration. In recent years, developing tool based on the collaborative work of citizen has been applied on the evaluation of geotechnical hazard and landslides [93,94], archeological prospecting [95] and the management of heritage landscapes affected by climate change [96]. Currently, this research team is working on a tool that identifies buildings pathologies through photographs using machine learning and citizen science. However, include them in Art-Risk 3.0 model require further studies their intervention, they must include long-term preventive conservation plans [57].

4. Conclusions

The results obtained demonstrate the functionality of the *Art-Risk3.0* methodology in the risk analysis for the conservation of heritage buildings quickly and through online and on-site work. Art-Risk3.0 allows quick identification of the threats present within a context thanks to the use of GIS. Furthermore, the adaptation of the different measurement scales according to a hazard index of 1–5 allows for a quick interpretation of how the considered variables influence the conservation of heritage buildings in the Spanish context.

As a methodological model, *Art-Risk3.0* differentiates the issues of hazard and vulnerability as showcased by the cases analyzed. *Art-Risk 3.0* enables decision-making for the preventive conservation of heritage buildings and their sustainable or emergency management following a natural disaster.

In parallel, the study carried out identifies thermal stress and torrential rains as the factors that most impact the national context most frequently and with greatest intensity. The hazard of frost, although to a lesser degree, also presents problems, especially in locations far from the coast. In turn, building maintenance and the state of conservation are the factors that most determine the vulnerability of the buildings analyzed.

In the modelled scenario, the difficulty associated with controlling factors such as torrential rains and thermal oscillation make it necessary to bolster the resilience of buildings to ensure their preservation. Reviewing the proper functioning of the roofs, the drainage network and improving ventilation are essential activities to minimize the level of risk to which buildings will be subjected in the future.

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