



# How to evaluate and mitigate vulnerability of historical buildings. A Spanish project experience

RIVUPH and ART-RISK projects implemented new approaches based on multidisciplinary analysis of environmental hazards and vulnerability in order to develop global conservation strategies. Such strategies can both minimize the deterioration of monuments and reduce the cost of isolated interventions, contributing to the preservation of cultural heritage

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**H**ow should we preserve historical heritage against floods, earthquakes or human actions? Images of Louvre museum during the flood in Paris in 2016 have shown the need of being prepared to know which monuments could suffer these types of accidents and which monuments are more vulnerable. In fact, our cultural heritage is continuously threatened by hazards of different kinds and intensity. Against those threats, we should know how to prioritize our actions and face emergencies. Studying hazards and vulnerability of our cultural heritage is one of the ways that we have to evaluate, and possibly mitigate, those threats to our historical heritage.

## Introduction

Monuments and their artworks are elements that belong to the history and tradition of a country. They are also a high source of economical income and represent the level of social-economic development of a region. However, most of the historical infrastructures endure continuous deterioration. This is caused by the steadily increasing atmospheric contamination, management problems and severe damage caused by natural accidents or the lack of respect by people. Therefore, the knowledge of vulnerability of our monuments against exceptional (floods, earthquakes, fires, vandalism, wars, etc.) or continuous (contamination, climate change, thermohygro-metric conditions, etc.) threats allows the analysis of risk probability and intensity in order to take the needed awareness-rising measures for the conservation of historical heritage. Reducing risk to cultural heritage

is a wide-ranging field that includes the analysis of threats at different scales and scenarios, from a country to a statue. Most studies are carried out on archival materials or well-known artworks in museums, due to the fact that insurance costs have risen dramatically in the last decade. But what happens to the monuments of our cities? This is one of the questions that we are trying to answer with our research. Whole monuments or cities are rarely studied under a risk methodology and their analyses are usually based on the assessment of main risks. New approaches are currently being developed to analyze multi-scenario risks for monuments in a city [1], with a huge bulk of data and scenarios that demand simplified models for decision-makers.

## Risk versus vulnerability: Two concepts linked

Concepts regarding risk and vulnerability were defined, in 1993, by the European committee for the defense of cultural heritage [2]. Vulnerability is the level of tenacity or weakness of a monument that faces outside hazards, even if these threats have a different origin: natural disasters, actions caused by meteorological agents, and human actions. Risk depends on both factors, because an ill monument is more vulnerable, and increases the probability of infection with an illness (threat). In summary, the degradation of monuments could be due to the effects of: structural damages, weathering affection, pollution agents or other anthropogenic factors; whereas the conservation degree of each monument is vulnerability, its evaluation is an indirect function of the level of deterioration.

Preventive conservation implies knowing the risks that a monument is subject to and acting over the causes of these risks (hazards and level of vulnerability). Considering the great number of non-desired events that could cause damage to a monument, the difficulty resides in the possible need of classifying and prioritizing, as well as being prepared to face a range of extreme situations.

The knowledge of risks and hazards are based on experience and the archive of past and ancient episodes and disasters. Risk management tries to use this information to decide the best strategies for preventive conservation. The current crisis leads to prioritize strategies in a town, as the urban unit where territorial policies could be applied, and moreover in a region where the restoration budget is distributed. For this reason our aim is to analyse a list of monuments in a city and give the order of intervention [1, 3-4]. Rivuph (start-end) and Art-Risk (start-end) are two Spanish projects developed to face this challenge:

**RIVUPH** ([https://www.upo.es/tym/en\\_rivuph.html](https://www.upo.es/tym/en_rivuph.html)) is a project of the Andalusian government (Spain) based on the analysis of environmental risk in historical cities in order to develop conservation strategies that can minimize the deterioration of monuments. With this purpose, multi-scenario risk maps of several towns have been drawn with Geographic Information System (GIS) software to provide information about the probability of the main hazards in a neighborhood. Hazards have been classified in three categories: 1) Static-structural hazards, that include

seismic factors, landslides, floods, coastal dynamics, avalanches, volcanic activity, underground water, geotechnical factors, etc. 2) Environmental-air hazards as erosion (wind, rain, sea, or river), pollution (vehicle congestion, traffic roads, industry, etc.), weather (rain, temperatures, dew points, etc.); and vibrations. 3) Anthropogenic factors (fires, accessibility to the monument,

have the following questions: how to carry out an accurate evaluation on different buildings in the same city? Have different technicians the same opinions about the vulnerability? Is the citizens' opinion different from experts' considerations? Guess that you have the responsibility to maintain all the building of a city and your budget is not enough (real situation stressed during this crisis), which

to simulate their reasoning and knowledge. As different experts have different opinions, this is the base of value of a DELPHI methodology. We combine this methodology with a double entrance matrix that allows to evaluate the conservation degree, that is vulnerability.

- **Fuzzy logic.** This method allows to evaluate the range of opinions of each expert. In contrast with

	Town/City (Inhabitants)	Carmona (28,679)	Estepa (12,397)	Osuna (17,800)	Marchena (19,768)	Seville (702,355)	Mitigation Action
	Monuments studied	19	17	20	11	30	All monuments must be under yearly surveillance and global maintenance plan
Vulnerability Evaluation	Very low damage (<10%)	6	6	8		1	Preventive maintenance plan and periodic inspections
	Low (10-25%)	11	9	10	9	13	Preventive maintenance plan and periodic inspections with minor interventions
	Moderate (25-50%)	1	2	2	2	15	Further studies and likely intervention in a long period
	High (50-75%)	1 (Alcazar)				1 (Sagrario)	Intervention is recommended in a short period of time (6-12 month)
	Catastrophic/ Very High damage (>75%)						Urgent Intervention (<3 month)
	Methodology applied	[1]	[1]	[1]	[1]	[3]	

Tab. 1 Evaluation of monument vulnerability and mitigation action proposal

tourist pressure, population, etc.). On the other hand, factors with potentially positive effects on reduction of monument deterioration have also to be considered; these elements can include town-planning protection. ART-RISK (<https://www.upo.es/investiga/art-risk>) is a project of the Spanish government based on the analysis of vulnerability, as the degree of a monument weakness. This evaluation needs the opinion of experts. But, after years of diagnosis for cultural heritage, you may

must be the first buildings to be restored or reinforced? Under this frame of questions, we proposed two different approaches based on artificial intelligence tools:

- **DELPHI Methodology.** This method is based on the prediction of experts, its name comes from the Greek sanctuary of Delphi, an oracle that was consulted on important decisions. Similarly, we consult a multidisciplinary group of 7-8 experts about their opinion of vulnerability and try

Boolean logic that only has two values (well or bad, yes or not), our diagnosis language has plenty of possibilities between a well- and a bad-conserved monument, for instance the roof is well conserved but we have problems of capillarity. Fuzzy logic allows us to evaluate these differences and, as an artificial intelligence tool, try to imitate the rationalization of experts.

Weighted factors were obtained consulting the multidisciplinary group

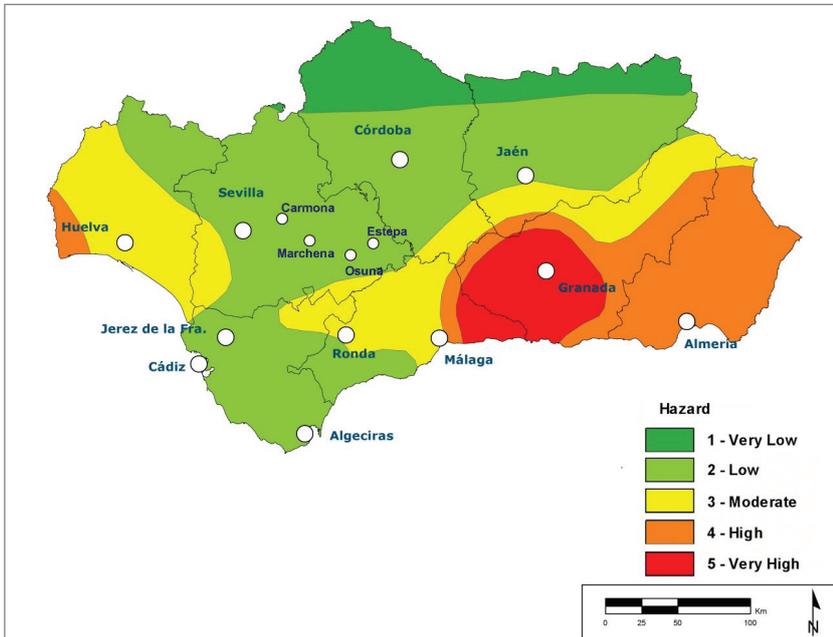


Fig. 1 Seismic hazard map of Andalusia (Spain)

### Evaluation of vulnerability in Monuments of Andalusia (Spain)

Vulnerability has been evaluated in more than two hundred monuments in Andalusia (South Spain). This diagnosis has allowed to develop a cognitive diagram of the relationships between different variables and the vulnerability index to improve the method of risk analysis. Conditions of foundation, structure and constructive systems have the highest weight when evaluating vulnerability according to experts' opinion, as these variables could produce a partial or total loss of monuments and their artworks, especially in seismic zones. Physical-chemical characteristics, texture and fire-resistance define the conservation degree of materials and have a medium influence, which is mainly dominated by nature and quality of materials. Aesthetic appearance has the lowest influence in the opinion of experts and citizens. Other variables as simplified building, urban planning protections and level of usage have to be also assessed, according to the type of construction, local and/or regional law and data of tourism office and owners [3].

As an example, Table 1 summarizes the evaluation carried out in well-known monuments of Marchena, Osuna, Estepa, Carmona and Seville. These five cities have historical centers, and the monuments chosen belong to the Roman, Muslim or Christian periods.

75% of the monuments assessed exhibited a very low or low degree of vulnerability, which means a vulnerability evaluation of less than 25%, so they would need a preventive maintenance plan and periodic inspections with minor interventions. Two monuments (Alcazar in Car-

of experts to evaluate the influence of each hazard and to overlap the factors in the risk map, and to evaluate the illness of the buildings. Under this objective, it is clear that risk analysis following from the evaluation of cultural heritage needs experts from different countries and specialties, as well as opinions of citizens that enjoy, use the monuments, or simple live near them. Consequently, we are using the social network to validate the opinions of experts and to improve the methodology ([http://www.upo.es/tym/rivuph/en\\_encuestas.php](http://www.upo.es/tym/rivuph/en_encuestas.php) or <http://www.ecomimesis.com/analisis-vulnerabilidad-patrimonio-historico>). Expert consultations and social network analysis have allowed to develop a new validated criteria based on the Delphi method, that forecasts the evolution of a provided situation asking their opinion to a limited number of experts [1]. This methodology has been used to consider the hazards and/or vulnerabil-

ity of several monuments of historical cities.

These assessments of threats imply collecting, georeferencing, weighting according to Delphi results and overlapping data from local, regional and national institutions of weathering, risk, environment, urbanism, territorial governance, sociology statistics, tourism, geology, hydrogeology, etc.. On the other hand, vulnerability needs an on-site study, where the frequency and weathering degree were taken into account. Although it is not possible to have every hazard in the same city, this general approach allows us to know the main risk and compare the results obtained in different cities for regional decision-makers. Meanwhile, each hazard has a frequency and intensity that varies according to the environmental conditions in the different districts of the city. This data is useful for local decision-makers.

mona and Church of Sagrario in Seville) have the highest vulnerability evaluation, due to important structural problems, which means they must be the first to be restored or reinforced against structural threats. Intervention is recommended in a short period of time (6-12 month). First floor and basement of Sagrario are now under restoration study due to their collapse.

Twenty-two of the monuments present moderate vulnerability, which according to the uncertainty associated with this methodology implies further studies.

In general, the vulnerability evaluation stressed that these cases were mainly affected by impacts associated to continuous erosion (humidity, change of temperature and wind pressure), anthropogenic interventions, vandalism and pollutants.

About pollution, it is worth emphasizing that the most common stones in these five cities are calcareous sandstones, calcarenites and limestones that are especially vulnerable to road-traffic pollutants.

The overlap between vulnerability and the main threats provides further information at the regional or local level. As an example, Figure 1 shows the risk map due to earthquake in Andalusia: the cities studied have low risk of earthquake, but repetition of episodes as the earthquake of Carmona (1504) and Lisbon (1755) could have important consequences for the buildings with medium or high vulnerability, so it is important to reinforce structures at least in the Church of Sagrario. In fact, some weathering forms detected during vulnerability evaluation in Monuments of Seville, Carmona and Estepa highlighted stability influence. In any case, vulnerability evaluation and mitigation strate-

gies must be updated in the case of changes or interventions, and it is advisable to repeat the analysis at least every three years or after disasters such as floods, fires, earthquakes, etc.

At the local scale, the multiscenario analysis of the cities showed that the maps of risk in Estepa and Carmona were dominated by landslide hazards, due to the presence of clay minerals around the edge of the hills. In Carmona, this risky area is just where the Alcazar is located, the

and 2c show, respectively, a zoom of the georeferenced map of static-structural hazards and the hazard map for road-traffic in the area of Sagrario and Cathedral of Seville.

Figure 2b shows, in orange and yellow, that the block of Sagrario/Cathedral has a medium-high risk of floods and damage due to capillarity humidity [5]. Meanwhile other monuments, such as Church of Santa Ana (STA), have a high vulnerability due to the effect of capillarity and they must have an evacu-

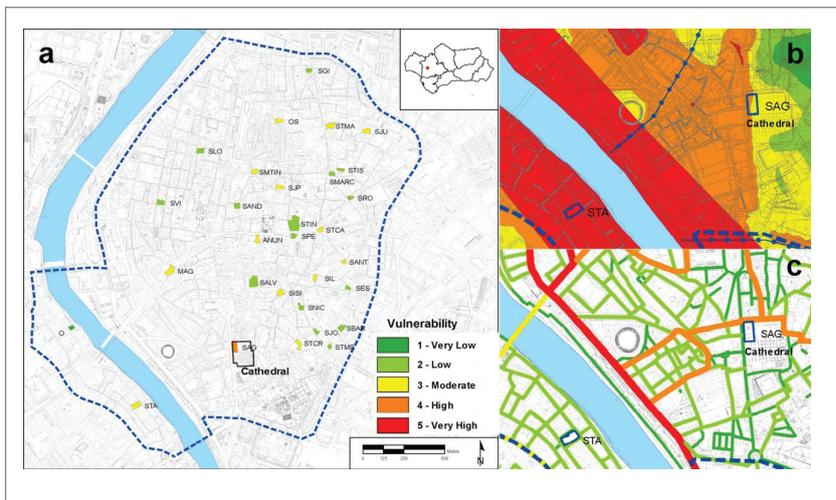


Fig. 2 Map of vulnerability of the monuments studied in Seville (a); a zoom of the georeferenced map of static-structural hazards (b); the hazard map for road-traffic in the area of Sagrario and Cathedral of Seville (c)

risk of landslides added to its high vulnerability index, and earthquake possibilities worsened the situation and demonstrated the necessity of interventions and special conservation with inspections and checking in the Alcazar.

The study of hazard maps, overlapped with vulnerability of Seville, has been chosen as an example of local study (Fig. 2). Figure 2a shows the map of vulnerability of the monuments studied in Seville. Figures 2b

and 2c show, respectively, a zoom of the georeferenced map of static-structural hazards and the hazard map for road-traffic in the area of Sagrario and Cathedral of Seville. Figure 2b shows, in orange and yellow, that the block of Sagrario/Cathedral has a medium-high risk of floods and damage due to capillarity humidity [5]. Meanwhile other monuments, such as Church of Santa Ana (STA), have a high vulnerability due to the effect of capillarity and they must have an evacu-

calcareous stones employed in both buildings.

To mitigate this effect, the five cities require an urban plan for vehicle traffic control to avoid driving near the main monuments, in order to decrease the weathering due to traffic pollution.

Another factor to analyze is the adoption of urban protection measures. As an example the detailed evaluation of urban planning in the city of Marchena [6], theoretically a positive factor, evidences the loss of buildings that should have been protected. The public administrations were informed of this irregular situation in 2012, but unfortunately we do not have evidence that any action has been taken since then. So it is necessary to improve the instruments of control and the inspections over the local authorities.

## Conclusions

In summary, the vulnerability evaluation methodology is an artificial intelligence tool that reproduces the opinion of experts to evaluate the conservation degree of a monument and allows to prioritize future interventions to mitigate the damage. This methodology, based on the overlapping of hazards and vulnerability elements, is very useful to identify, evaluate and prioritize the restoration interventions in a city and to address preventive conservation also in the region by using a scientific approach.

This procedure provides protocols to develop policies for decision-making when preservation of historical centers is needed. This methodology allows to compare risks between different cities to ana-

lyze strategies for cultural heritage conservation in a region, or inside a city, and evaluate the hazards of different zones in order to establish mitigation plans.

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