**VULNERABILITY ANALYSIS AND RISK MAP OF CULTURAL HERITAGE.
THE CASE OF THE HISTORICAL TOWN OF MÉRIDA, SPAIN.**

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ABSTRACT

The risk assessment of the damage, which can undergo the historical heritage, is very useful for its conservation. The risk maps give information about the probability of the main hazards in a region. These risk maps are tools to be used to identify, evaluate and prioritize the restoration actions on a degraded monument and to forecast the preventive maintenance budget, and they even allow political strategies for the conservation. As a good risk assessment needs of a large number of risk variables and vulnerability parameters to be analyzed and compared, these studies are impractical due to the excessive time consumption, and the high cost of the analysis. For this purpose, GIS (Geographical Information System) are usually employed. This technique has some obvious advantages to the risks analysis application for cultural heritage conservation, such as the capability of simultaneous risks assessment and geographical references. On the other hand, the vulnerability study implies the conservation analysis in situ, and it needs adapted protocol for archaeological heritage.

In this study, we present the first results of a project for the risk assessment of the historical town of Mérida (Spain). A GIS application (ArcGIS software) has been used to reference and a vulnerability index has been employed for the analysis of the conservation degree of three monuments: the Arch of Trajan, the Aqueduct of the Miracles and the Roman Bridge).

INTRODUCTION

1.1 *Background*

The World Heritage List includes 890 properties forming part of the cultural and natural heritage which the World Heritage Committee considers as having outstanding universal value. A lot of different hazards can affect these sites what means that frequently the disaster management has to deal with Cultural Heritage problems, such as preservation, safeguard, reconstruction, etc.

It is possible to conceive two different risk typologies for Cultural Heritage runs. The first one is the normal decay due to age which is a low traumatic but continuous action; the second one refers to isolated impulsive events (earthquakes, floods, contamination, anthropogenic risks, etc). A whole knowledge of the objects, buildings and sites is the correct approach to face these two sorts of risk and it is able to lead both the common planning maintenance, and possible restorations.

The general guidelines for the risk assessment of natural disasters are stated by the United Nations Disaster Relief Organisation of UNESCO [1]. Hazard is defined as the probability that a phenomenon, of an established intensity, may occur in a defined area during a given period of time. Vulnerability can defined as the degree of loss of elements at risk as a consequence of the occurrence of a natural phenomenon of a given intensity. The risk corresponds to the expected value of loss of elements due to hazards and it can be expressed as the product of hazard and vulnerability.

Many methodologies and integrated tools have been developed for hazard assessment and risk analysis. An approach to major industrial hazard assessment was described for the Venice Port Authority in Porto Marghera [2], an industrial estate near Venice (Italy). Industrial hazard concerns was solved through an interactive tool COMPARE (COMPuter Aided Risk Evaluation), a prototype of an integrated tool for developing hazard assessment and risk evaluation [3]. Probabilistic model for multi-hazard risk assessment can also be found in a literature review [4]. An origin-pathway-target model for contamination applied for both resource and source protection was proposed by COST Action 620 in the Pan-European Approach, which was studied as the first application of all components of this approach [5].

Scientific researches have also been carried out on evaluations of environmental hazard and risk applied to historical sites. Geomorphologic hazard and risk with regard to landslides, floods and erosion processes have been described for archaeological sites in Italy [6] and integrated GIS-based approach to evaluate the state of conservation-decay of the architectural heritage and its interaction with natural-anthropological components have been studied in Tursi [7], one of the most representative sites of the cultural heritage of Basilicata (southern Italy).

An integrated assessment about risk maps of Italian Cultural Heritage has been built by the ICR (Istituto Centrale per il Restauro) [8]. In this project, alphanumeric and cartographic data about environmental hazard and the vulnerability of the historical sites have been compiled in a geographical information system (GIS) capable of exploring, superimposing and processing information concerning potential risks in order to get protection, safeguard and preservation of Italian Monuments and Archaeological Sites.

In this context, the aim of the present work is to perform the Risk Map of Mérida, a city located in the western Spain, which Archaeological Ensemble is listed on UNESCO World Heritage since 1993. An aggregated hazard, an integrated vulnerability analysis and finally an aggregated risk map for Mérida's Cultural Heritage were carried out in order to evaluate the conservation, preservation and restoration of the monuments.

1.2 *Case study*

Mérida city was founded by order of Roman Emperor Augustus in 25 BC under the name of Emerita Augusta for veterans of the legions Alaudae V and X Gemina.

Soon after, the new Roman colony was designated as the capital of Lusitania province. During this period the city will become increasingly important in the Hispanic context, reflected in the monumentality of its main buildings (circus, theatre, amphitheatre, bridges, aqueducts, etc.).

Figure 1 shows three of these monuments that have been studied in this project. Arch of Trajan and the Roman Bridge were made with granite blocks and mortar and the above materials in addition to brick were used to build Aqueduct of The Miracles.

Figure 1: City of Mérida. Aqueduct of The Miracles, Roman Bridge and Arch of Trajan.

METHODOLOGY

In order to analyse the risk monuments of Mérida a combination of two methodologies have been utilised. Models of Baldi *et al* [8] have been used to the construction of hazard maps of the studied area. For the analysis of the weathering degree a vulnerability matrix have been carried out according to Galán *et al* [9] with several modifications.

This research implies three different phases according to the project promoted by the ICR methodologies:

1. Knowledge of the Monuments
2. Hazard Assessment
3. Vulnerability Analysis

1.3 *Knowledge of the Monuments*

A bibliographical study have been carried out on the city of Mérida, to acquire information concerning the history, valuation and distribution of cultural heritage to know the present situation and to decide the covered area for the approach. The studied area for this work is 10 km^2.

The first step of the work has been focused on the analysis of the built heritage of the city in order to geo-reference them in a database.

1.4 *Hazard Assessment*

Hazards have been classified in three categories following ICR methodology. Static-structural, environmental-air and anthropogenic factors were evaluated in the historical city of Mérida.

Hazards studied for Mérida were the following: floods, underground water, geotechnical factors, wind, river and rain as erosion elements, vehicle congestion, traffic roads, industry, rain, temperatures, dew, theft, vandalism and tourist pressure. Several factors with positive effects have also been considered, such as vegetal barrier to protect the monument from pollution, weather protection shelter and town-planning protection.

Data has been obtained from AEMET (Agencia Estatal de Meteorología) [10], IGME (Instituto Geológico y Minero de España) [11] and CEDEX (Centro de Estudios y Experimentación de Obras Públicas) [12].

Each hazard has a given frequency and intensity that can vary in accordance with the particularities of the city. The frequencies and intensities of hazards in Mérida have been determined utilising a relativity scale with a maximum of five levels.

These hazards are then utilised to obtain three different types of individual hazard maps (structural, environmental and anthropogenic). ArcGIS software is the tool to plot the hazard in the space.

Individual hazard maps are multiplied by a weighted value depending on its magnitude. Weighted factors have been got using the Delphi process and consulting a multidisciplinary group of seven experts (archaeologists, geologists, chemists, architects, engineer s and environmentalists). Finally, the aggregated hazard map is obtained by adding the three individual hazard maps with their corresponding weight values [13].

1.5 *Vulnerability Analysis*

To determine the vulnerability of each monument, a vulnerability matrix (VM) has been developed and adapted to suit the nature of Heritage conservation problems of Mérida monuments according to Galán et al [9].

The degradation of the building materials, evaluated by means of the vulnerability index (*VI* %), is mainly due to the deterioration effects of static-structural damage, weather and pollution agents and anthropogenic damage. The VM is prepared by inserting in the rows the hazards of the particular environment and in the columns the building material characteristics, the structural conservation degree and aesthetic properties.

Weathering forms have been described according to CNR-ICR Norma 1/88, [14] and Fitzner [15]. These pathologies are included in a preliminary VM of qualification. Impacts have been identified and characterized and each matrix cell has been associated to stone deterioration patterns.

The vulnerability index for each monument has been quantified by a visual study of the buildings, where the frequency and weathering degree of the deterioration patterns is taking in account.

In this study, the frequency of appearance is set between 1 and 3; if it is difficult to detect the presence of the weathering form the frequency would be 1, if the weathering form is identified easily, the frequency would be 2 and the frequency would be 3 if it occurs at a high rate.

On the other hand, weathering degree quantification is classified in five relative classes, according to scale used by Fitzner. Level 0 means no damage, and level 1 is a low damage and 4 is a very high damage. Non-damage zones have not been plotted. Frequency and damage are combined in the table 1 in order to obtain a numerical value of the intensity of weathering forms in each monument.

After the study of the weathering forms, the vulnerability index (*VI*) is calculated dividing the total value of the deterioration patterns (V_x) for a monument by the sum of total value of deterioration patterns in the worst case ($\sum vdp$), when the frequencies would be 3.

$$VI = \frac{Vx}{\sum_{f=3} vdp} x100$$

Table 1: Intensity of deterioration patterns.

	Low Frequency (1)	Medium Frequency (2)	High Frequency (3)
Low damage (1)	1	2	3
Moderate damage (2)	2	3	4
High damage (3)	3	4	5
Very high damage (4)	4	5	6

Finally, vulnerability index (*VI%)* is classified into vulnerability degrees using ordinal classes described by Galán *et al* [9] (table 2). This vulnerability degree is geo-referenced in a vulnerability map.

Table 2: Vulnerability degrees.

VI (%)	Vulnerability degrees
<10 %	Low
10-25 %	Moderate
25-50 %	High
50-75 %	Very high
>75 %	Catastrophic

1.6 *Risk Map*

The aggregated hazard map and the vulnerability map are combined in GIS application with the Delphi weighting (figure 2) to obtain the risk map. The new integrated risk map allows to distinguish between lowest and highest hazardous regions and to know the localization of the monuments with more vulnerability degree.

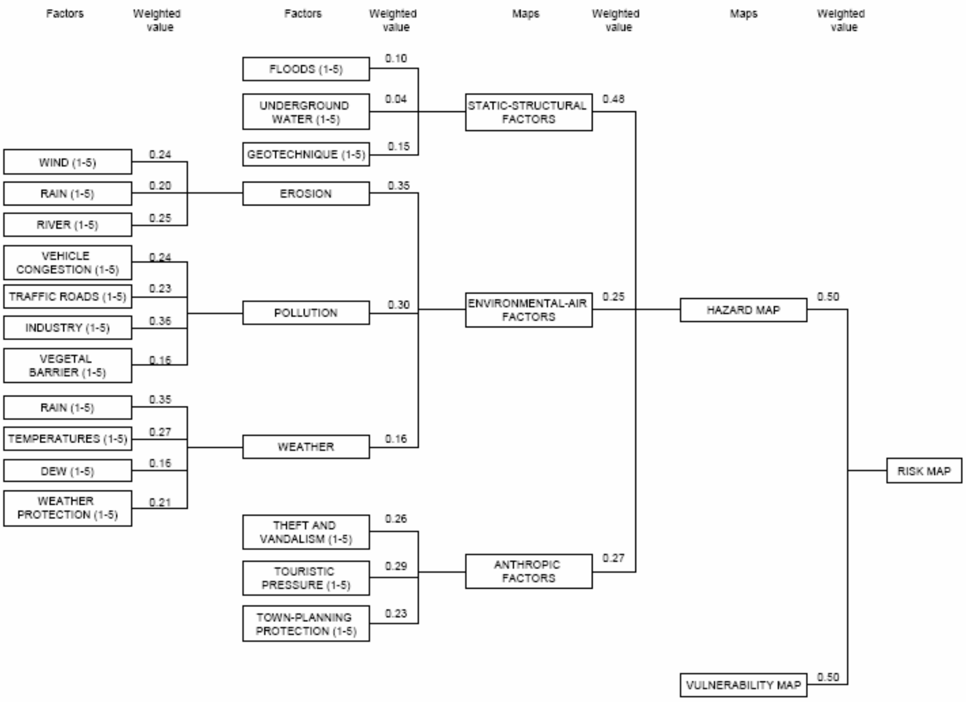

Figure 2: Delphi method.

In order to generate the aggregated hazard map of Mérida, every hazard have been geo-referenced and overlapped using the corresponded Delphi weighted value (figure 2).

RESULTS & DISSCUSION

Several sources have been consulted to obtain the information for the maps [10, 11, 12]. The static-structural map (figure 3) has been built considering floods, underground water and geotechnical factors. The figure 3 shows that the main structural problems are due to the river and the city area of Mérida presents a low level of static-structural hazard.

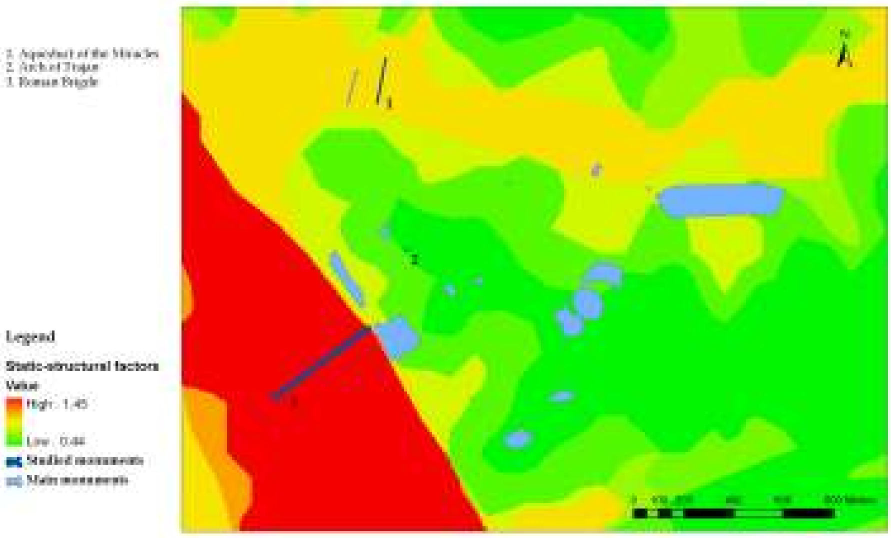

Figure 3: Static-Structural Hazard Map of Mérida

Environmental-air map is built overlapping erosion, pollution, weather and vegetable barrier factors (figure 4). In this map, it is possible to observe that more important environmental-air problems are due to river erosion and the proximity to traffic roads.

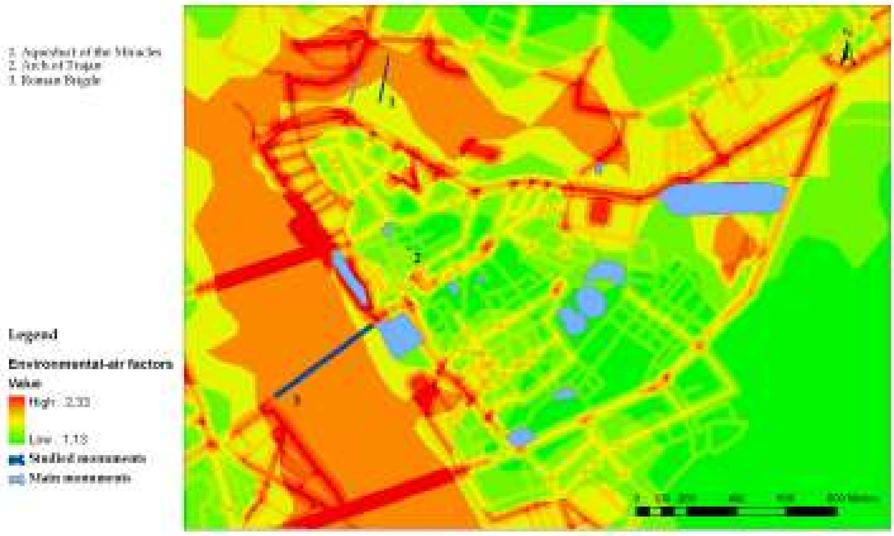

Figure 4: Environmental-Air Hazard Map of Mérida

Anthropogenic map have been carried out with theft, vandalism and tourist pressure data from the government of Mérida and the town-planned protection layer (figure 5). This map shows a large area of low hazards (green colour) that is just over the Monumental City, it is due the positive effect of the town-planned protection.

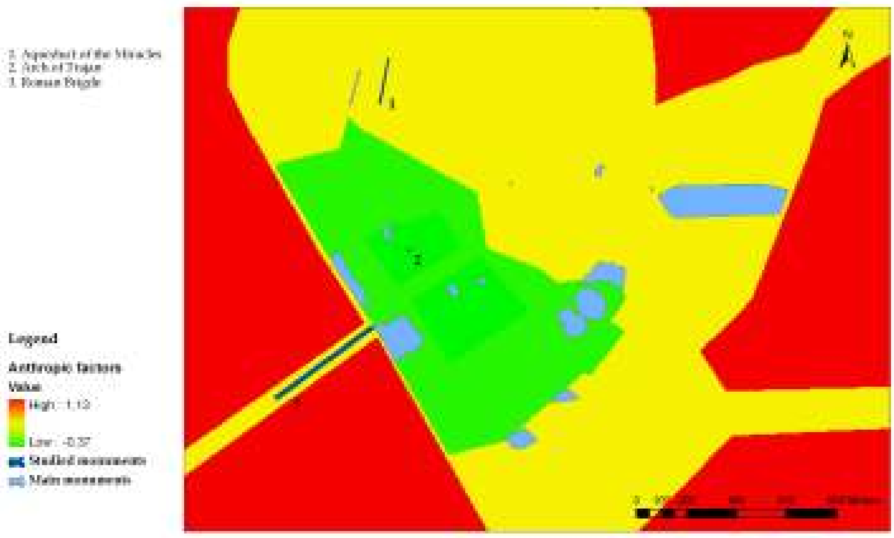

Figure 5: Anthropogenic Hazard Map of Mérida

Finally, the three hazard maps are overlapped to obtain the integrated hazard map (figure 6). This Map is dominated by the hazard due to the presence of the river in the city.

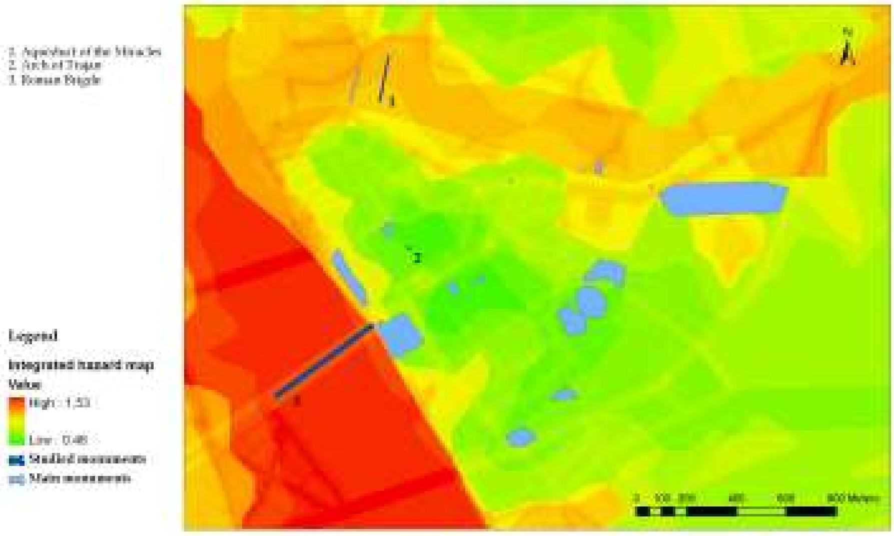

Figure 6: Integrated Hazard Map of Mérida.

The vulnerability index of three monuments (Arch of Trajan, Aqueduct of The Miracles and Roman Bridge) is studied by the frequency and quantification of weathering forms. The main weathering form in the three monuments is loss of fragment. This deterioration has a frequency of three and it is very common in every building materials. Erosion has also been detected in the three monuments with high frequency. The Arch of Trajan and the Aqueduct of The Miracles have high level of deposits and moderate level of arenization. Staining due to vandalism and biogenic crust are found in the Roman Bridge and salt efflorescences are easily found in Arch of Trajan. Soiling, vegetation and encrustation are examples of low-moderate frequencies of weathering forms.

Monuments studied are well preserved and the main weathering form observed is loss of fragment due to age and surface deteriorations patterns.

According to previous observations, vulnerability index have been estimated in table 3 and consequently vulnerability degree results are shown in table 4 for each monument. The monument with the lowest vulnerability (5%) is Aqueduct of The Miracles, and the Roman Bridge and Arch of Trajan have moderate vulnerability between 11-12%. Those results implies that the conservation state of the Arch of Trajan and the Roman Bridge make themselves more vulnerable for extrinsic factors than the Aqueduct of The Miracles, though they are well maintained in general.

Finally, this vulnerability of the monuments is added to the aggregated hazard map in order to obtain the risk map of Mérida for the three monuments studied. The aggregated hazard map and vulnerability degrees map have been overlapped according to Delphi weight and the results of the risk analysis are plotted in figure 7.

Table 3: Vulnerability index calculation

			MATERIAL CHARATERISTIC										
			MATERIAL						BUILDING STRUCTURE				
			CHEMISTRY COMPOSITION	TEXTURE	POROSITY / PERMEABILITY	THERMAL CONDUCTIVITY	FIRE RESISTENCE	SURFACE ALTERATION	FOUNDATION	BULINDING STRUCTURE	CONSTRUCTION	VISUAL APPEARANCE	**TOTAL**
HAZARDS	SOIL CHARACTERISTICS	GEOTECHNIQUE											
	UNDERGROUND WATER												
	DISTANCE TO THE RIVER												
								10				10	20
	WEATHER	WIND						9				9	18
								8				8	16
								9				9	18
		TEMPERATURES						6				6	12
								6				6	12
								6				6	12
		RAIN	4	4	4	4		10				10	36
								4				4	8
								15				15	30
		DEW						6				6	12
								5				5	10
	NATURAL RISKS	FLOODS											
	POLLUTION AGENTS							3				3	6
								3				3	6
								1				1	2
	ANTHROPIC ACTION	POPULATION											
		TOURISTIC PRESSURE											
		BUILDING WORKS						3				3	6
								2				2	4
	USE	LEISURE PLACE											
	MONUMENT SECURITY	THEFT AND VANDALISM											
								2				2	4
		OTHERS						1				1	2

Note:
1. [grey cell] Theoretical impacts
2. Each row is divided in three cells, the first one is for Arch of Trajan, the second one is for Aqueduct of the Miracles and the third one is for Roman Bridge.

Table 4: Vulnerability degree of the three monuments studied.

Monument	VI (%)	Vulnerability degree
Arch of Trajan	11 %	Moderate
Aqueduct of The Miracles	5 %	Low
Roman Bridge	12 %	Moderate

The highest value of the risk is around two in the city Mérida and is dominated by the hazard due to the presence of the river. This value is moderate in relation to the ordinal scale used for the study, where the maximum is five.

Roman Bridge has a risk value of 1.72 because it presents the highest vulnerability and it is placed in the most hazardous area. The risk value of Arch of Trajan is greater than risk value of the Aqueduct of The Miracles (1.35 and 1.09 respectively). Although surroundings of Aqueduct of The Miracles are more hazardous than surroundings of Arch of Trajan, the vulnerability of the previous one is lower than the Arch and therefore the risk is greater in this case. The vulnerability of the Arch of Trajan can be associated to the fact that the cars cross it nowadays.

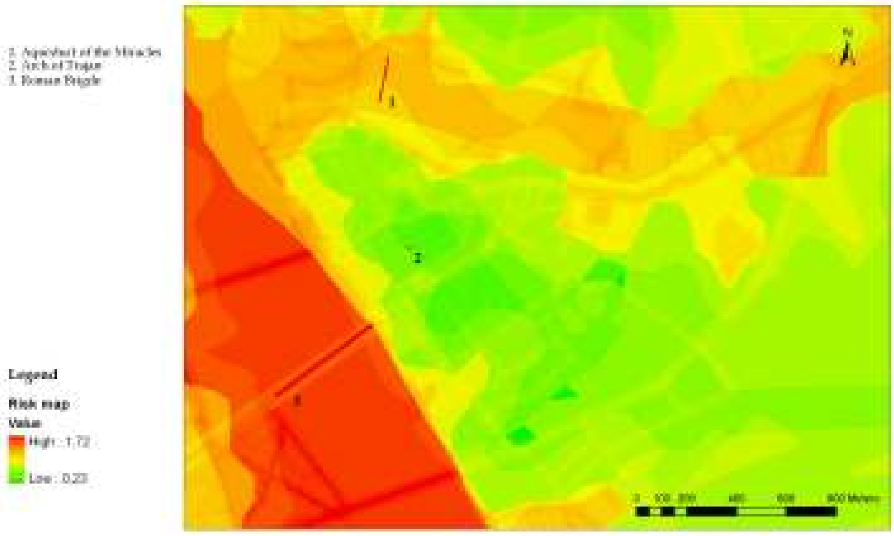

Figure 7: Risk map of Mérida

According to this study, the Roman Bridge is located in a risky area because it has the highest vulnerability and it is in the most hazardous area of the city. Although the bridge has a good conservation management because it is isolated from traffic roads, it is over the river and the action of water and the stability of the area must be taken in account in the future, especially during floods.

CONCLUSIONS

Mérida is a city with a high structural stability where the main hazards are related with the river and pollution; meanwhile weather conditions are not very risky. Anthropogenic hazards are very low because theft and vandalism are not very frequent and this kind of problems emphasize only in monuments with a significant influence of tourists.

In addition to these external factors, Anthropogenic hazards became less significant due to the town-planning protection of monuments in Archaeological Ensemble area and weathering factors are soften for the shelter of some monuments.

This paper presents an easy and cheap methodology that allows to know the main hazards of a city and the conservation conditions of monuments and provide tools for helping to decide which factors should be considered more important in preservation efforts and which monuments need a clear intervention plans.

Preliminary results obtained showed the capability of this tool to discriminate among the hazards in relation with the location of the monument. Moreover they provide the experimental evidence that Geographical Information System and Environmental Impact Evaluation can be very effective and efficient to the purpose of performance Risk Map of Cultural Heritage.

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