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Approach to environmental risk analysis for the main monuments in a historical city

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ABSTRACT

The analysis of environmental risk in historical cities facilitates the development of conservation strategies that can minimize the deterioration of historical heritage sites. Risk maps built with GIS software provide information about the probability of the main hazards in a region, and is a very useful tool to identify, evaluate and prioritize the restoration budget of a city in order to manage preventive conservation. In this paper, new methodologies are applied based on the vulnerability matrix and its relationship with static and structural factors, climate conditions, air quality and social agents. This technique has some obvious advantages in the application of risk analysis for cultural heritage conservation, such as the capability of simultaneous risk assessment and geographical references. The vulnerability study implies an on-site diagnosis analysis and requires an adapted protocol for archaeological heritage. The validation of this methodology was carried out in the historical town of Merida (Spain) with a GIS application (ArcGIS software), where the main monuments of this UNESCO World Heritage site were studied.

1. Research aims

Nowadays, large budgets must be allocated to restoration due to continuous environmental hazards or following disasters. The research aim of this paper is to analyze a new methodology to prioritize restoration and to know the main risks of cultural heritage cities. To this end, vulnerability matrices are used to evaluate the degree of conservation, and hazard maps are applied to understand weathering agents. The results are overlapped with GIS software to have georeferenced information pertaining to historical cities.

2. Introduction

Frequently, unusual environmental conditions have a disastrous impact on the conservation of cultural heritage sites; however, normal conditions also bring about the slow degradation of building materials. In this respect, two different risk strategies can be found: the first one is a continuous action due to the ravages of time and the second one is associated with isolated events (earthquakes, floods, fires, etc). A recent example of a disaster is the earthquake measuring 5.8 on the Richter scale that took place on 5th April 2009 with its epicenter in L'Aquila, a walled city located two hours from Rome. Among the monuments that were most affected were the Basilica of Santa Maria de Collemaggio, the church of Saint-Augustine and the Church of the Holy Souls. It was also a catastrophic situation for the State Archives, housed in the National Museum. Floods affected several historical cities in the Czech Republic in August 2002. Cesky Krumlov, included in the list of UNESCO Cultural Heritage, was one of the most damaged cities. The fire of 25th August 2006 at the Cathedral of the Holy Trinity in Saint-Petersburg (UNESCO Cultural Heritage since 1990) caused the collapse of two of the five domes, including the main one. These disastrous events have been widely studied; however, longer-term environmental processes, such as pollution or rainfall, are rarely considered as hazards, though they are the cause of major restoration spending. For this reason, thorough knowledge is required of the conservation state of buildings in historical cities and the environmental factors surrounding them.

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

The first risk map assessment was developed by the ICR (Istituto Centrale per il Restauro) [2]. Now, there are specific applications and projects using integrated tools for hazard assessment and risk evaluation [3–5] but uses of GIS incorporating efficient

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storage, management and analysis of spatial and non-spatial data are limited [6,7], although GIS-based environmental assessments are widespread [8,9]. Landslide and rockfall related to the geomorphology of an area are two individual hazards commonly studied with this methodology [10–13]. However, natural disasters often involve simultaneous multiple hazards that are best evaluated in connection with the concept of vulnerability. The latter is a key factor in understanding the potential destruction of monuments by natural disasters [14]. De Lange et al. [15] also developed a framework for vulnerability in ecological risk assessment where anthropogenic and natural hazards, along with their impact on an ecosystem are linked by vulnerability. Hazards may result in short-term perturbations or long-term disturbances depending on the vulnerability of the ecosystem. In a cultural heritage approach, the system is the city or the area where monuments are located, but the relationship between hazard and vulnerability could be assumed to be similar.

When a number of hazards are considered in a GIS-based risk assessment, probabilistic models and multicriteria analysis can be achieved through the overlaying of thematic maps [16–18]. Multicriteria decision-making employs the concepts, approaches, models and methods that aid an evaluation, expressed by weightings, values or intensities of preference [19], which ultimately may lead to better decisions. Halpern et al. [20] and Coppolillo et al. [21] produced comparable results using the Delphi method, also called expert judgment, in ecological risk assessment and Zhong-Wu et al. [22] have recently studied the relative importance of hazard mapping in an integrated eco-environment assessment based on GIS. Multicriteria decision analyses are widely used for urban planning scientific investigations based on evaluations of environmental hazards and risks applied to historical sites. Natural hazards have also been assessed using a GIS-based approach for archaeological sites and the cultural heritage of cities [23–26].

The vulnerability of buildings has been studied using different methods. Examples of these are the evaluation of the state of conservation/decay of architectural heritage sites and their interaction with natural-anthropological components through a vulnerability index [27] or by georeferencing the internal environmental differences within buildings [28].

Accordingly, this paper aims to demonstrate a new methodology to evaluate the risk map of a city, integrating alphanumeric and cartographic data about environmental hazard and the vulnerability matrix of the monuments in a compiled information system (GIS).

3. Materials and methods

3.1. Study area

The UNESCO world heritage city of Merida located in southwest Spain is the site of this study. Merida was founded by order of the Roman emperor Augustus in 25 BC under the name of Emerita Augusta for veterans of the Alaudae V and X Gemina legions. Soon after, the new Roman colony was designated the capital of Lusitania province. During this period, the city became increasingly important in the Hispanic context, reflected in the monuments of the city. Nowadays, many buildings from that period are still standing in the city. The area studied for this paper is 10 km^2 and the eighteen most emblematic monuments have been taken into account when applying the vulnerability analysis.

3.2. Acquiring information

Knowledge of the monuments and a study of their environmental conditions are essential for risk assessment. The analysis of each monument in the city focused on location, era, role played, building materials, general description, digs, restorations, protection in urban development, deterioration patterns and other incidents. Environmental data were obtained from AEMET (Agencia Estatal de Meteorología) [29], IGME (Instituto Geológico y Minero de España) [30] and CEDEX (Centro de Estudios y Experimentación de Obras Públicas) [31]. All the information was used to construct a georeferenced database.

Data from the Guadiana river basin organization have been collected and show major flooding in the city in the 1970s and 1990s [32]. The last flood took place in 2010 during this study [33].

3.3. Vulnerability analysis

The degradation of building materials and structures is mainly due to the deterioration effects of static-structural damage, weathering, pollution agents and anthropogenic damage. To determine the vulnerability of each monument, the vulnerability index (*VI%*) was calculated based on a vulnerability matrix (*VM*) similar to the one reported by Galán et al. [34], but adapted to suit the nature of heritage conservation problems specific to the monuments of Merida.

The vulnerability matrix was prepared by inserting the hazards of the particular area of the city in the rows and the building material characteristics, degree of structural conservation and aesthetic properties in the columns. Weathering forms were described according to CNR-ICR Normal 1/88 [35], Fitzner [36] and the ICOMOS-ISCS glossary [37]. These characteristics were included in a preliminary classification vulnerability matrix (Table 1). The vulnerability matrix for hazards in Merida is shown in Table 1. Each impact (matrix cell) is described with all the potential weathering forms that could be found in a monument of the city.

The vulnerability index for the eighteen monuments chosen was determined by an on-site study, where the frequency and weathering degree of the deterioration patterns were taken into account. In this study, the index was evaluated for the predominant lithotype.

The frequency of weathering forms was set between 1 and 3:

- frequency 1 if it was difficult to detect the presence of the weathering form;
- frequency 2 if the weathering form was identified easily;
- frequency 3 if it occurred at a high rate.

The degree of weathering was classified into five relative categories, according to the scale used by Fitzner [36]. Level 0 means no damage while levels 1 to 4 range from low-level damage to very high damage. Frequency and damage level were combined as shown in Table 2 in order to obtain a numerical value for the intensity of weathering forms in each monument.

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

$$VI = \frac{V_x}{\sum_{f=3} vdp} \times 100 \tag{1}$$

Finally, the vulnerability index (*VI%*) was classified by degree of vulnerability using ordinal classes as described by Galán et al. [34]: very low (< 10%), low (10–25%), moderate (25–50%), high (50–75%) and very high vulnerability (> 75%). The vulnerability degree for each monument was georeferenced on a vulnerability map.