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Above the Ravines: Flood Vulnerability Assessment of Earthen Architectural Heritage in Quito (Ecuador)

Francesca Trizio [1,*], Julio Garzón-Roca [2], Miguel Ángel Eguibar [3], Paola Bracchi [4] and Francisco Javier Torrijo [1,5]

[1] Research Centre PEGASO, Universitat Politècnica de València, 46022 Valencia, Spain
[2] Department of Geodynamics (GEODESPAL), Faculty of Geology, Complutense University of Madrid, 28040 Madrid, Spain
[3] Department of Hydraulic Engineering and Environment, Institute for Water and Environmental Engineering (IIAMA), Universitat Politècnica de València, 46022 Valencia, Spain
[4] Facultad de Arquitectura, Diseño y Artes, Pontificia Universidad Católica del Ecuador, Quito 170143, Ecuador
[5] Department of Geological and Geotechnical Engineering, Universitat Politècnica de València, 46022 Valencia, Spain
* Correspondence: fratri@upvnet.upv.es

Abstract: Floods represent one of the most threatening risks for earthen architectural heritage. Developing risk assessment tools is considered crucial to mitigate the risk and to protect heritage buildings. Due to its hygroscopic nature, earthen architecture is generally considered to be vulnerable to water, requiring a specific analysis. This paper proposes a vulnerability assessment method for earthen buildings in flood-prone areas. Based on the evaluation of the susceptibility of the building's components and characteristics, the method allows for quantifying the vulnerability of the assets, in non-monetary terms. An application of the methodology is carried out assessing a selection of earthen construction in Quito Historic Centre (Ecuador). The results show the influence of each component in the global vulnerability of the earthen buildings. The response of different construction techniques and the importance of the maintenance of heritage buildings is exposed. Vulnerability assessment methods at the meso-small scale constitute the foundation for risk assessment. Thus, this study aims to provide a significant assessment tool that can be used for further analysis and future lines of research, aiming to protect cultural heritage that is at risk.

Keywords: floods; earthen architecture; vulnerability assessment; world heritage site

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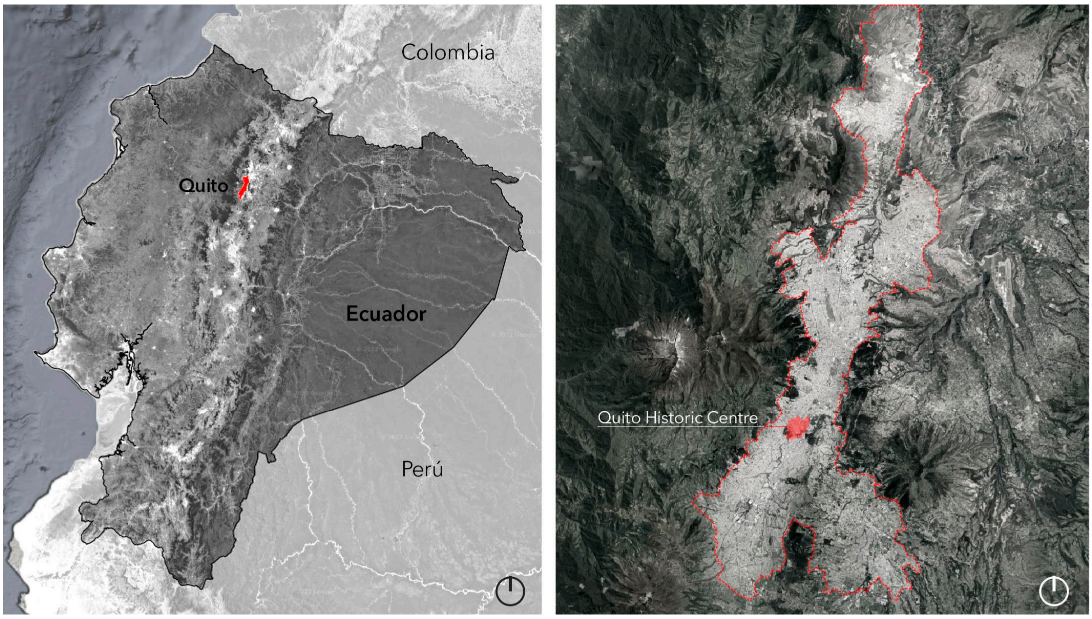
1. Introduction

Earthen architecture is generally considered susceptible to the action of water. Due to its hygroscopic nature, earth as a construction material can be affected by rising dampness, resulting in the loss of hydromechanical resistance [1,2]. Floods pose a threat to architectural heritage, as they can cause direct and indirect damage to structures or the collapse of buildings [3,4]. The importance of protecting architectural heritage from flooding has been recognized internationally in the 2015 Sendai Framework for Disaster Risk Reduction [5]. In this context, risk assessment is considered a crucial tool for developing management and prevention plans. Most of the studies related to flood risk are based on economic analyses and quantifications that, in the case of heritage assets, are hardly applicable. It is worth mentioning that in the insurance industry, when referring to natural risk evaluation, vulnerability relationships are also known as damage functions, implicitly emphasising economic damage [6].

In the case of cultural heritage assessment, this task becomes challenging due to the variability of the characteristics of the assets [7,8]. Architectural and cultural heritage is composed of several values: artistic, historical, and commemorative [9]. Therefore, an assessment only based on monetary variables may not be exhaustive. The complex value of a cultural asset needs an equally complex index, which also considers potential non-monetary losses [10,11]. Several studies developed specific risk assessment methodologies for heritage assets, based on a non-monetary analysis [12–14], and simplified vulnerability methods were developed for large-scale assessments [13,15], which form the basis for further analysis carried out at a local scale [16,17]. In recent years, some studies dealing with the assessment of earthen heritage sites were carried out [18–20]. Du et al. [21] applied the fuzzy-AHP and AHP-TOPSIS to assess the damage level for 18 earthen sites of the Ming Great Wall. Other works delved into the weathering and durability of earthen material and structures [22], their mechanical characteristics, and structural behaviour [23,24].

This paper focuses on assessing the vulnerability of earthen architecture to floods by applying a component-based methodology. The demonstration of the methodology is provided by the assessment of the historical centre of Quito (Ecuador). The city of Quito occupies an area of 19,000 ha, 4.5% of its metropolitan district, which has an extension of approximately 423,000 ha (Figure 1), is located on the slopes of the Pichincha volcano at 2850 m a.s.l. and is surrounded by the hills of Panecillo, Itchimbía, and San Juan. Quito represents a striking example of a Spanish colonial settlement founded in 1534. The ancient city sat on a platform of about two kilometres per side. Three large ravines crossed the platform, and their branches—now practically disappeared under the ground—collected the copious amount of rainfall on the Pichincha [25].



(a) (b)

Figure 1. (**a**) Site map of Ecuador. Scale: 1:8,000,000; (**b**) Site map of Quito. Scale: 1:500,000.

In this geographical context, floods occur during the rainy seasons, i.e., between November and May, and they are caused by localized and short rainstorms that do not usually last more than two hours but that lead to overflows in rivers and ravines. Rainfall patterns are very heterogeneous as a result of the combination of several geographical factors, such as height, orography, and the winds crossing from the Pacific and the Amazon. On the eastern slope of the Pichincha, several dozen ravines descend to the city to reach the Machángara River or the Monjas River. These ravines are ephemeral streams characterized by an intermittent flow regime which can reach 20 m deep. The natural transit of liquid and solid discharges through these streams has been gradually blocked, filling the ravines over time and building collectors at important depths, which in some cases can exceed 25 m. However, despite recent improvement interventions, the current sewage network is not adequately sized for the flow it receives. In recent decades, urban growth is affecting high-risk urban areas, the edges of the ravines included. The phenomenon is injuring the geological components of the territory, causing the weakening of the soil and leaving the slopes uncovered and unprotected. Together with such wild building processes, land exploitation, intensive agriculture, and inappropriate use of watersheds also influence the increase in the frequency and intensity of catastrophic events. The study carried out by P. Peltre [26] on the ravines and natural disasters in Quito, states that from 1900 to 1988, the city was affected by 233 floods, which corresponds to an average of three events per year. According to more recent reports developed from the data recorded by the Integrated Security Service of Ecuador, the metropolitan district of Quito experienced 804 floods between 2005 and 2014 [27]. The relationship between the city, the ravines, and the associated risk generates technical-infrastructural, urban-spatial, and architectural-cultural issues [28]. Such problems affect, to a greater extent, the historical centre of Quito, which was declared a World Heritage site by UNESCO in 1978 for its multiple cultural values. The historic centre extends over 375 ha and comprises 14 neighbourhoods, where more than 5000 buildings are recorded as heritage assets [29].

In addition to the architectural variety that characterizes this historical centre, it should be noted that colonial buildings are Hispanic patio houses and more than 50% are built with earthen techniques, such as adobe, rammed earth and half-timber [28]. This heritage site has been classified as a "high-exposure" flood-prone area [27]. The most recent floods, such as those of March 2019 and 2022, that caused severe damage to immovable assets and the population, highlight the high level of risk to which Quito is exposed [30]. From this perspective, the concept of the "historic urban landscape is not limited to the built heritage but also includes other components, such as the geomorphology, hydrology, and infrastructures that shape the urban structure and give identity to a place. For the historical centre of Quito, the topography and hydrology play a fundamental role, so considering these components is essential for conserving its architectural heritage. Therefore, assessing the heritage assets within their context is necessary to create the foundation for risk mitigation and management plans.

This paper addresses this issue by proposing an approach to establish the vulnerability levels and classify each building according to the vulnerability value obtained. The use of an analytical matrix provides a complete and significant overview of the typological and structural characteristics of the buildings, as well as their state of conservation. Thus, the detailed study of the material weathering and structural damage and its correlation with floods is fundamental to developing the conservation measures that comply with the 2011 UNESCO recommendations on historic urban landscapes [31]. The implementation of a vulnerability map using GIS technology will also set the basis for developing more convenient conservation actions in cost-benefits terms.

2. Materials and Methods

The vulnerability assessment of earthen heritage buildings was carried out through a component-based methodology. Risk is generally considered the combination of hazard, exposure, and vulnerability. This study focuses on the quantification of the vulnerability of heritage buildings. Frequently, this task becomes difficult due to the frequent lack of information on the characteristics of these heritage assets. This study uses a component-based assessment method to quantify each element's vulnerability. To this purpose, the susceptibility factors were defined. Moreover, the weighting coefficients obtained with the Delphi method were applied to each parameter [32]. This type of hybrid empirical assessment, based on expert judgment and analytical studies, is widespread for small-scale analyses. At this tier of assessment, the parameters are defined on building characteristics and conservation states. Following the methodology developed by RISK-TERRA Project for a large-scale risk assessment [32,33], a method for assessing the level of vulnerability on a small scale was designed. The research was organized in three phases, presented at the following sections.

2.1. Research Area

During the first phase of research, a territorial analysis was carried out to identify the area most affected by flooding risk. Through the study of maps and historical documentation, a hypothetical trace of the course of the ravines was reconstructed, whose footprint today is not visible on the surface. According to the historical sources, three streams influenced the process of the urban development of the founding nucleus of the city of Quito. The ravine of the southwestern end, called Ulluguangayucu, successively known as Jerusalem, closed the city by this sector, running at the foot of the Panecillo Hill. On the other side, from the foot of the mountain of San Juan to the south, ran the Huanacauri Ravine. Between these two ravines, the deepest one ran, known as Sanguña and later as Tejar, due to the presence of tile ovens in its proximity. This ravine descended from the slopes of the Pichincha volcano, joining the Placer Hill in the current Ipiales market, and known by the name of Manosalvas and its eastern end. From the XVII century, these ravines were filled very fragmentarily until the XX century, when the final projects of channelling and coating were conducted. Thus, the three ravines that descend from the foothills of the Pichincha constitute one of the most important conforming elements of the city. Up to the XIX century, the perimeter ravines and the temporality of the roads or trails hindered the implantation of a stable grid. The blocks built on the beds of the ravines have an irregular shape, which stand out from the general structure of square blocks of 90 m on each side. Thus, the city has been developing on the ravines. In some cases, the footprint is perceived in the layout of the streets, created as a result of fillings over time; in other cases, the traces of the ravines seem to disappear in the urban grid, leaving space for the full conformation of the blocks. Although these ravines are not visible, they continue to affect the architectural heritage because of the capillarity of the groundwater, as well as the consequences of floods in periods of maximum rainfall when water descends from the slopes of the Pichincha volcano. Through the reconstruction of the course of the ravines and the use of the flood vulnerability map of the disaster risk management plan for the central nucleus of the historic centre of Quito [34], the map of the area most exposed to flood was obtained. Figure 2 shows the hypothetical course of the ravines (dark grey) over the grid of the city.

Figure 2. Map of the most exposed area with the hypothetical course of the ravines. Scale: 1:8500.

2.2. Cases Studies

The second phase of the research focused on selecting the most relevant buildings for the analyses. Despite the great extension of the area, its urban and morphological homogeneity stands out. Throughout the site, the repetition of architectural and formal types can be observed, both in traditional dwellings and in monumental constructions. It is also noted that the traditional morphological characteristics have been preserved despite the transformations that occurred during the process of the evolution of the city. Within the urban grid, structured by the minor architecture, the monumental elements, representative and symbolic landmarks of the city, are inserted juxtaposing to the houses, creating a contrast that results in a harmonious sight to the viewer, who receives the image of a coherent city and at the same time enriched by a lot of architectural and artistic diversity. This coherence is generated both by the treatment of the compositional elements and by the use of traditional materials, such as adobe, mud, brick, lime, clay tiles, and wood. Fifty-eight percent of the beams of the buildings are made of wood and 40% of the walls are made from adobe [35]. The architectural expression in the colonies is always the result of a process of transculturation. The coexistence of diverse cultures gives rise to new needs, and to satisfy the new parameters, is required. Housing is a very striking example of this process of miscegenation between American and Hispanic cultures. As the conforming element of the urban grid, housing is configured as a reflection of the society of a people, and its characteristics clearly show how the imported elements were adapted to the local context, both in their climatic and geographical conditions, as well as in the social and cultural ones. Unlike religious architecture, where it is recognizable as a direct representation of the culture of the conquerors (Figure 3), who faithfully followed the European models for the consolidation of their ideology, the transposition of these models to residential architecture is not marked.

Figure 3. Church and Convent of San Francisco, Quito. Code: QU-1. (2022).

Depending on the social and economic level of the houses, a greater or lesser application of Spanish styles is visible. The characteristics of the Spanish architecture prevail in the palaces, while for the construction of the popular houses, few resources encouraged the combination of the Spanish and autochthonous architectural traditions. The consolidation of Spanish architecture in Quito took place during the seventeenth century. During this time, the model of colonial residential architecture was generated, and this is today recognized as Quito architecture (Figure 4a).

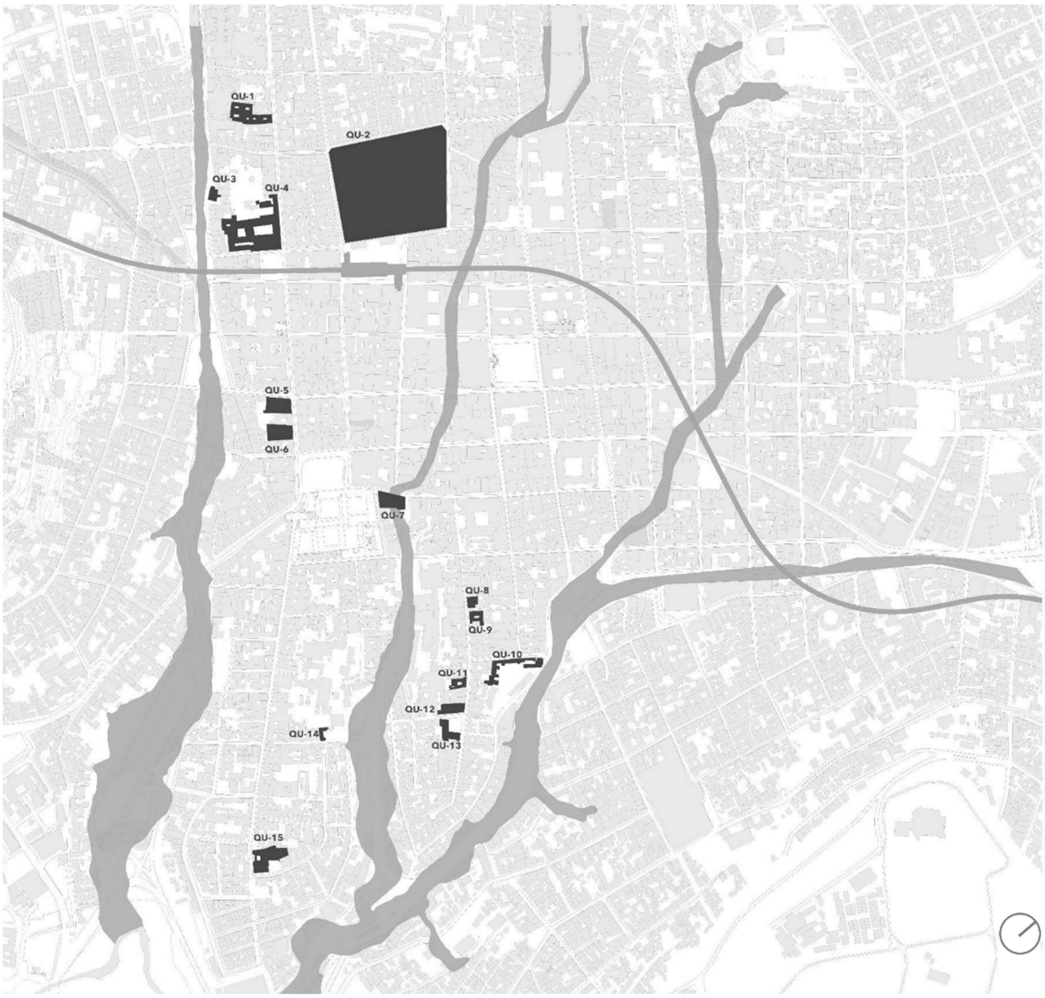
(a)

(b)

Figure 4. (**a**) View of traditional houses, Quito, 2022; (**b**) Hispanic patio of the Ecuadorian Museum of Architecture (MAE), Code: QU-8, Quito, 2022.

Thus, the Quito traditional house was born, whose model was mainly the Hispanic house, which was built around a central element, the patio, surrounded by a portico and rooms (Figure 4b). The access was facilitated through a hallway in a straight line and perpendicular to the street. The balustrade was found in front of the entrance and the main rooms on the sides. Through a passageway, the main courtyard was put in communication with the backyard where the environments for the easement and the oven were located. Behind the backyard, the orchard was found. For the construction of colonial houses, various techniques and materials were used. The load-bearing walls were adobe or brick, which had similar dimensions. It should be noted that the adobe, whose dimensions could vary between 45 cm × 20 cm × 10 cm and 60 cm × 30 cm × 15 cm, was manufactured according to the indigenous tradition with soil and chopped straw, letting it dry in the sun, which provided resistance. These walls unloaded on the large foundations of stone ashlars to avoid problems of fissures and cracking in the adobes. All of the walls were plastered with ground mud on a layer of earth and straw, as well as the ceilings of the rooms.

In order to obtain scientifically significant results, a sample of 15 earthen buildings exposed to risk and considered relevant for the purposes of the analyses, based on their historical and architectural value were selected (Figure 5). The sample consists of residential and religious buildings that represent the heterogeneity of Quito architecture from colonial times to the first decades of the XX century (Table 1). Despite the typological differences, all of the case studies are built with adobe walls with earth joints and a plinth made of ashlars. The necessary information for the analysis was obtained, based on the existing literature about the historic centre of Quito [25,36]. The information collected was completed through fieldwork sessions. The case studies were catalogued into descriptive forms that summarize the graphic and historical information found. Subsequently, the necessary data for the vulnerability assessment was selected and added to the digital map file, thus creating an attribute table in which the characteristics of each case study appear. The practical implementation of the vulnerability assessment methodology for the selected case studies is described in the following section.



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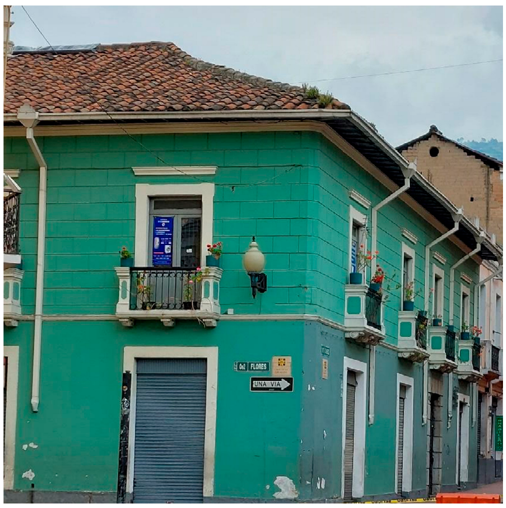


(**c**)

Figure 5. (**a**) Case study map. Scale: 1:8500. (**b**) Picture of a religious building. (**c**) Picture of a residential building.

Table 1. List of the selected heritage buildings.

Code	Building	Type
QU-1	Casa de los Siete Patios	Residential/Commercial
QU-2	Church and Convent of San Francisco	Religious
QU-3	Capilla del Robo	Religious
QU-4	Monastery of Santa Clara	Religious
QU-5	Casa de Luis Robalino Dávila	Residential/Commercial
QU-6	Casa Ponce	Residential/Commercial
QU-7	Casa del Puente de Manosalvas	Residential/Commercial
QU-8	Museo Arquitectura Ecuatoriana (MAE)	Residential/Cultural
QU-9	Casa Ortiz Bilbao	Residential/Administrative
QU-10	Colectiva Almeida	Residential
QU-11	Casa de Mathias Abrams	Residential
QU-12	Casa de la Fundación Caspicara	Residential/Institutional
QU-13	Church of San Marcos	Religious
QU-14	Capilla de los Milagros	Religious
QU-15	Mama Cuchara Cultural Centre	Residential/Cultural

Note: The first type corresponds to the original use, the second to the present use.

2.3. Vulnerability Assessment

The vulnerability assessment methodology used was based on the identification of the components of earthen buildings and their susceptibility. The latter is defined as the potential damage that each component may suffer as a result of a flood, considering its main physical characteristics. Thus, flood vulnerability can be defined as the degree to which an asset is susceptible and unable to cope with the adverse effects of flooding. The estimation of the susceptibility was the result of a study of the existing literature on the characterization of the earthen architecture and the effects of the action of water on its materials [1,22,37]. The construction characteristics of the asset and the relationship with its environment was considered, as well as the state of conservation, which represents an influencing factor for potential damages. Each susceptibility factor was assigned a value of 1 to 5, depending on its response to the action of floodwater, where the value of 1 corresponds to a low susceptibility and 5 to a high susceptibility. The global resistance of a wall highly depends on its construction technique. The more a wall is monolithic and homogeneous, the more it will have resources of resistance against the action of horizontal hydrostatic pressure that generates overloads, proportionally, to the height of the water. Thus, a minimum susceptibility value (1) was assigned to rammed earth walls, whereas adobe and half-timber walls were assigned medium (3) and high (5) values. In addition, the different variants of each construction technique were assigned values between 1 and 5, according to the previous consideration. The metric characteristics of the building (footprint and number of floors) represent the size of the building and its responsiveness to water drag. The position of the building related to the ground level, as well as its building type, have a great influence on the water drag and absorption. The function of the plinth at the base of the walls is also considered relevant. This construction element guarantees the separation of the walls from the ground, allowing to reduce the action of rising damp. However, the insulation provided by the plinth changes depending on its material. Ashlars plinths have a high cohesion and thin joints, thus their susceptibility to water is low, while brick and masonry plinths have a greater absorption rate which results in higher susceptibility values. The presence of an additional protection and of rendering can improve the resistance of the structure, according to the hygrometric characteristics of the material. The state of conservation of the buildings plays a crucial role. The more a material is deteriorated the more susceptible to the impact of water. Erosion processes and cracks facilitate the penetration of water and humidity, increasing the susceptibility.

Susceptibility values were corrected by weighting factors, obtained by consulting the opinion of 43 experts and applying the Delphi method [32,33]. The experts were selected from various fields (including architecture, engineering, restoration, geology, heritage, and conservation). They were asked to reply to a survey evaluating the influence of each characteristic on the buildings' behaviour, in the case of flooding, using a scale of 0 to 10. The average result of each weighting factor was calculated by applying the Chauvenet criterion [38] and a standard deviation of 2 was obtained. Table 2 shows the values assigned to the components and their weights.

Table 2. Earthen architecture susceptibility parameters.

Characteristic	W	SF	Characteristic	W	SF
Urban location	0.8		Construction technique	0.6	
- With basement		5	- Rammed earth		1
- Below ground		4	- Adobe		3
- Ground level		3	- Half-timber		5
- Above ground		1			
- Sloping ground		3			
Footprint [m^2]	0.4		Variants of the construction technique	0.6	
- 0–250		5	- Homogeneous rammed earth		1
- 250–500		3	- Supplemented rammed earth		3
- >500		1	- Mixed rammed earth		5
Floors	0.4		- Homogeneous adobe		5
- 1		1	- Supplemented adobe		3
- 2–3		3	- Mixed adobe		1
- 4–5		5	- Simple half-timber		5
			- Complex half-timber		1
Building type	0.4		Plinth	0.7	
- Freestanding		5	- No plinth		5
- End of block		4	- Masonry		3
- On a corner		3	- Ashlar		1
- Detached		1	- Brick		2

Table 2. *Cont.*

Characteristic	W	SF	Characteristic	W	SF
Additional protection	0.5		Rendering	0.5	
- yes		1	- No rendering		5
- no		5	- Earth		4
			- Earth and lime		2
			- Earth and fibres		3
			- Lime		1
			- Gypsum		3

Note: W = weight; SF = susceptibility factor.

These weighted values represent the influence of each component on the definition of the overall characteristic value of the asset.

The characteristic vulnerability index CVI for each asset was obtained using:

$$CVI_i = \frac{\sum_{i=1}^{n}(cs_i \cdot w_i)}{n} \tag{1}$$

where cs_i is the susceptibility value assigned to each characteristic of the components, w_i is the relative weight and n is the number of characteristics involved. The state of conservation of the assets was assessed by assigning susceptibility values and weighting coefficients to the most recurrent damages (Table 3).

Table 3. Damages susceptibility factors and weights.

Damages	W	SF
Wall erosion	0.7	
- Absent		1
- Superficial		2
- In the joints		3
- Diffuse		4
- Volumetric loss		5
Rendering erosion	0.5	
- Absent		1
- Superficial		2
- Partial		3
- Considerable		4
- Heavy		5

Table 3. *Cont.*

Damages	W	SF
Plinth erosion	1	
- Absent		1
- Superficial		3
- In the joints		4
- Volumetric loss		5
Structural damages	1	
- Absent		1
- Hair crack		3
- Minor crack		4
- Deep crack		5
Rising damp	0.6	
- Absent		1
- Present		5
Wall saturation	0.8	
- Absent		1
- Present		5

Note: W = weight; SF = susceptibility factor.

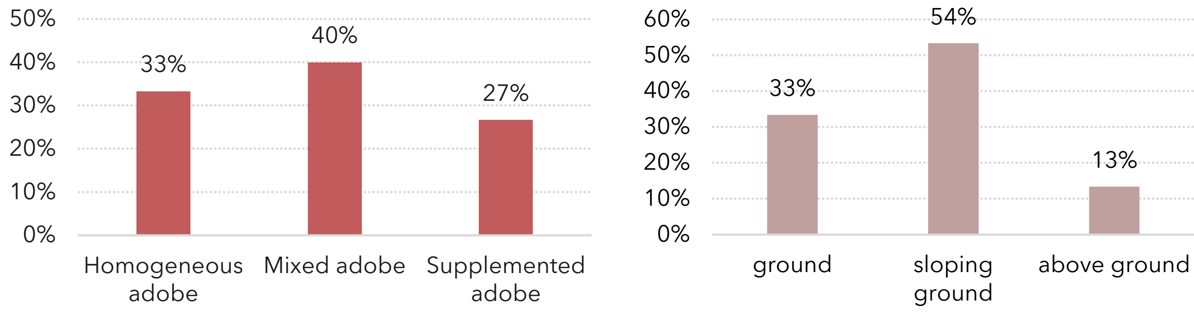
The vulnerability index related to the superficial and structural damage was obtained through the following equation:

$$DSI_i = \frac{\sum_{i=1}^{n}(ds_i \cdot w_i)}{n} \quad (2)$$

where ds_i is the susceptibility value assigned to each damage, w_i is the relative weight and n is the number of damages involved. These two indices (Equations (1) and (2)) were added together, obtaining the total index scaled in a range between 1 and 10.

3. Results and Discussion

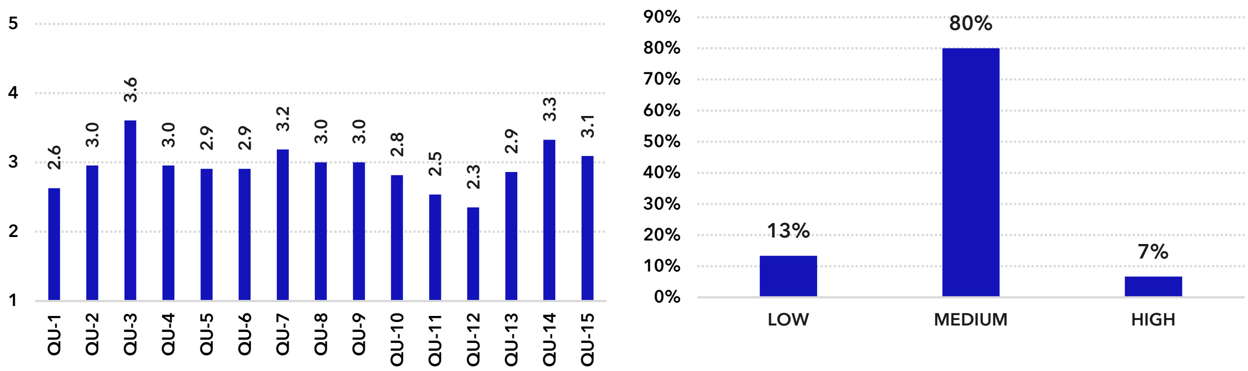
The results obtained through the application of the proposed vulnerability assessment methodology lead to highlighting some interesting topics for the understanding of traditional architecture, and more specifically, of earthen construction techniques. Buildings were chosen to obtain a sample diversified by the architectural typology, thus selecting five religious buildings and ten civil buildings of various dimensions and characteristics. As mentioned above, all of the buildings analysed have adobe walls. However, by collecting information and observing the buildings in situ, a detailed analysis was possible, differentiating three typologies of adobe walls: uniform, mixed (adobe and brick), and supplemented with brick corners. The data obtained show that most of the walls are made of adobe and bricks (40%), while uniform adobe walls and supplemented walls are, respectively, 33% and 27% of the total (Figure 6a). Another very influential feature for the purposes of the analyses is undoubtedly the topography of the site, which conditioned the construction of the buildings. More than half of the buildings are in an urban condition with an obvious inclination, a third of the cases are built at street level and a smaller percentage (13%) are built above ground, due to the presence of a platform with steps (Figure 6b).



(**a**) (**b**)

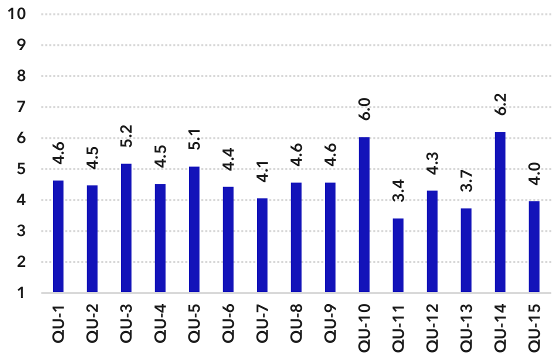
Figure 6. (**a**) Percentage distribution graph of the adobe construction system; (**b**) Percentage distribution graph of the urban locations of the assets.

These classifications are very important when it comes to understanding the results of the susceptibility assessment, as they allow for showing the weaknesses of the buildings, their resistance resources and their resilience. The vulnerability assessment turns out that the characteristic vulnerability index of the buildings varies in a range of values between 2.4 and 3.6 (Figure 7a), on a scale of 1 to 5. So, the vulnerability associated with the intrinsic characteristics of the majority of the assets can be assumed to be medium (Figure 7b). However, these values are not fully representative of the actual condition of the buildings. Thus, evaluating its state of conservation by calculating the susceptibility index associated with the damages was also considered essential. The values obtained from the combination of the two indices are included in a range of low and medium vulnerability, between 3.4 and 6.2 (Figure 8a). Looking at the percentage distribution of the values of the total index, 73% of buildings have a medium susceptibility index, 13% have a low susceptibility index, and 7% a high susceptibility index (Figure 8b).

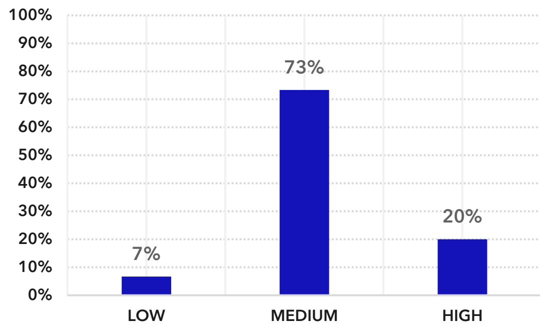


(**a**) (**b**)

Figure 7. (**a**) Characteristic vulnerability index graph; (**b**) Percentage distribution of the characteristic vulnerability index values.



(a)



(b)

Figure 8. (**a**) Total vulnerability index graph; (**b**) Percentage distribution of the total vulnerability index values.

Comparing the characteristic vulnerability and the total vulnerability, an increase in the value is observed. This increase is caused by the state of conservation of the asset, significantly changing the value of the index. For instance, if the QU-3 and QU-10 cases are analysed, QU-10 is noted to have increased its value, exceeding QU-3, and this is related to the presence of forms of material weathering and damages affecting the walls. In fact, in almost all buildings, forms of deterioration were found, especially due to rising damp. This result is very striking because it is in direct correlation with the presence of the channelled and filled ravines, whose projected canalization works underestimating the flow they receive, causes problems of infiltrations in the soil. However, the analysis turns out that the wall supports on ashlar plinths are a construction feature, can be considered a resource of resistance for the constructions, as they counteracts rising damp.

The graph in Figure 9 shows the comparison between different adobe construction techniques: uniform walls are those with the highest susceptibility rates and in the highest percentage; mixed walls show a variety in their values, although most of them are in an intermediate susceptibility range; finally, the indices obtained for the supplemented walls warn of a medium-high range of vulnerability. These last data should be understood, by taking into account that they are the result of a weighted calculation influenced by the state of conservation of the structures. The results highlight the importance of carrying out successive studies, evaluating the assets at a detail tier of the analysis (Figure 10). In fact, the importance of the heritage assets requires an in-depth approach for any type of risk management strategy.

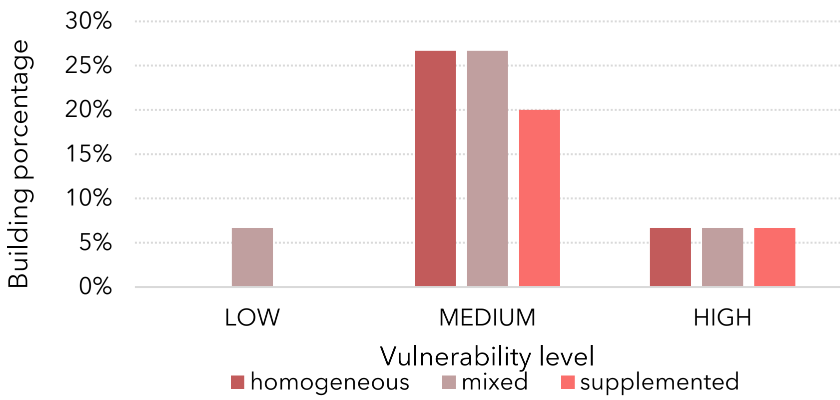


Figure 9. Comparison of the vulnerability index between adobe construction systems.

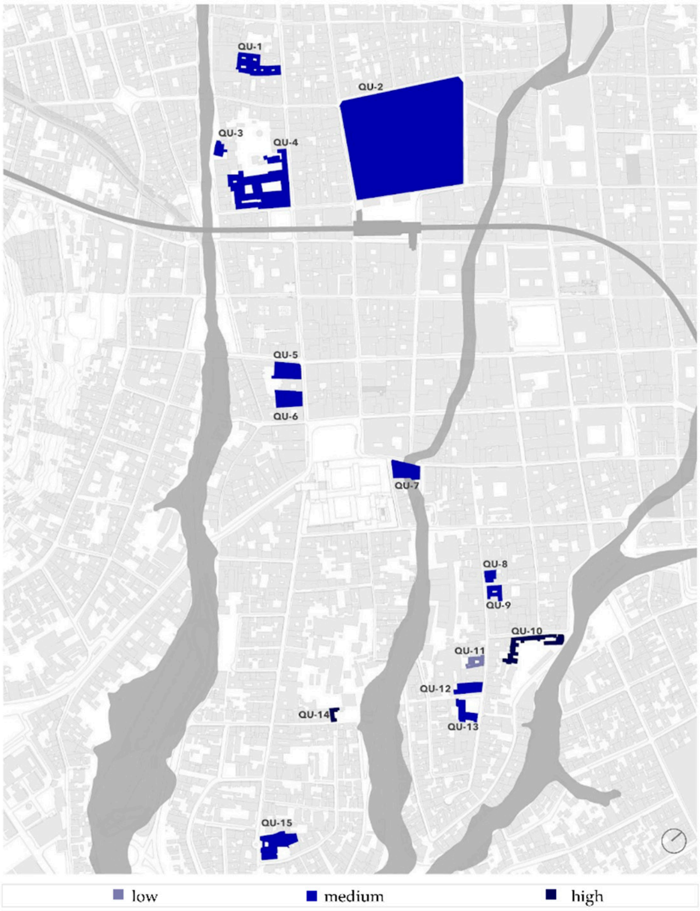


Figure 10. Vulnerability map of the Quito case studies. Scale: 1:8500.

The historic centre of Quito stands out among the urban complexes declared as World Heritage sites by UNESCO as it is a unique case of the harmonious interaction between urban development and natural environment. However, this extraordinary achievement of human ingenuity presents an intrinsic vulnerability, due to the topography and environmental constraints that generate a wide range of natural hazards. The need to protect heritage assets from natural hazards has been considered a priority only in recent years. Several actions have been promoted in terms of the risk management framework, in order to project and subsequently carry out risk prevention and mitigation strategies and measures. The proper knowledge of architectural assets is considered an essential resource in risk analysis, since it allows to differentiate the most vulnerable buildings, in order to carry out appropriate actions respecting their cultural and territorial values. The methodology applied in this study constitutes a proposal for the vulnerability assessment. For the identification of the limitations and future lines of intervention, undertaking a discussion on some fundamental aspects is necessary. Firstly, the vulnerability assessment proposed focuses on evaluating the potential and expected damages (or level of damage) that the assets could possibly experience when a flood occurs. Therefore, monitoring the assets at risk would provide information about their state of conservation and possible damages related to the effects of floods, providing evidence for the calculation.

This methodology provides an assessment tool for small territorial scales, such as historic centres, that is useful for the drafting of management plans, since it is applicable to multiple buildings. However, for the design of direct protection and conservation measures, the development of a more detailed analysis at the asset level is necessary, taking into account its material characteristics and metrics. In addition, as highlighted by de Moel et al. [39], when working at a meso/micro-scale, increasing our knowledge of the effects of floods on critical assets, is appropriate, due to their social and economic importance. It should also be noted that in the evaluation of historical and heritage assets for flood vulnerability, there is a certain level of uncertainty, due to the lack of information on the building characteristics. In general, a flood risk assessment implies several uncertainties related to meso-scale outcomes [40] with future scenarios due to climate change and global warming [41]. In the case of heritage assets, it is difficult to conduct a vulnerability assessment, due to the lack of post-disaster data. This difficulty is reflected in the impossibility of quantifying the damages in the event of an irreversible loss, due to the intangible nature of the value associated with the heritage. In this context, the qualitative [12] and quantitative vulnerability assessment methodologies [42] try to provide solutions to a complex issue that carries many implications. The results of these methods form the basis of the risk analysis and, consequently, of the risk management plans, through the definition of direct and indirect measures. In the case of the historic centre of Quito, the risk management plan [34] contains several lines of intervention, based on the following guiding principles: culture, as one of the pillars of human development, and resilience, understood as the ability of a system to adsorb the disturbances and acquire a new state of equilibrium. Moreover, some fundamental objectives were considered: to preserve the universal values of the historic centre of Quito and to protect its urban and cultural landscape, ensuring its integrity for future generations. To this end, the plan defines specific objectives, among which are indicated in the first place, the elaboration of strategic alignments in accordance with the guidelines established by UNESCO for the Management of world heritage risks and the execution of a threat analysis, considering the probability of occurrence (return period), as well as the magnitude of the impact on the heritage. Although the management plan constitutes an important tool for the development and protection of the historic centre, it does not provide detailed information for each risk detected. For a better response to floods, both prior to the verification of the disaster and a posteriori, developing specific plans and strategies for this specific risk are necessary, detailing the prevention, mitigation, and response actions that enable the safeguarding of the heritage.

4. Conclusions

This paper focuses on the flood vulnerability assessment of earthen architecture at the middle-small scale. The methodology proposed can be considered as a simple strategy to assess heritage assets exposed to flood risk. Its application to the historic centre of Quito reveals the level of vulnerability of its earthen architectural heritage, as well as the risk to which it is exposed. The actual territorial situation and the filling of the ravines have triggered several issues, such as diffuse rising damp affecting walls. It can be concluded that the combination of intrinsic vulnerability, due to the specific material and structural characteristic of the buildings, and the visible damages and material weathering can lead to further deterioration and the loss of the assets. To prevent this scenario, the accurate knowledge of the architectural assets is considered an essential resource in risk analysis, since it allows to differentiate the elements to be protected, in order to carry out appropriate actions respecting the cultural and territorial values of the architectural heritage. Moreover, the development of assessment tools, implementing a complete database of cultural heritage at risk, should be the foundation to carry out further analysis and intervention strategies. The implementation of structural and non-structural measures can increase the resilience of the buildings. These actions should aim to improve the environmental conditions of the site, as well as to improve the durability and structural characteristics of earthen heritage buildings. Thus, this study opens up to future research lines to develop an assessment methodology at the asset scale and design an appropriate flood mitigation and cultural heritage conservation strategies.

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