Analysis of Seismic Risk and Vulnerability of the Historical Context of Tehran with Emphasis on Resilience Zoning

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Abstract. Historical fabrics are recognized as national capital and tourism destinations worldwide. One of the most important threats to historical fabrics is the risk of natural disasters, especially earthquakes. Over the past two decades, Tehran's historical fabric has come under significant pressure due to rapid socio-economic growth, urbanization, tourism, etc. In this regard, spatial assessment, and zoning of seismic vulnerability in this area are considered fundamental requirements in earthquake impact reduction planning. This study aims to assess the vulnerability of Tehran's historical fabric using the MCDM approach and, in order to clarify the vulnerability status resulting from earthquake hazards and measure the resilience level in Tehran's historical fabric, earthquake risks of the fabric were first identified based on importance, intensity, and probability using the Delphi questionnaire, and weighted criteria by the FAHP method. In the next stage, the ELECTRE method was used to prioritize the resilience level of the four districts of this fabric and rank the potential earthquake risks. The results of the studies, as a resilience zoning map(Result of analysis in ARC GIS), show that more than 78% of Tehran's historical fabric area has been recognized with very high vulnerability which includes the Tehran city center and the central part of District 12. Furthermore, among the identified potential earthquake risks, the risks of increased density of the deteriorated fabric, severe lack or absence of urban open spaces, and high population density are ranked as the highest earthquake risks in this fabric.

Keywords: Vulnerability · Earthquake · Tehran's Historical Fabric · FAHP · ELECTRE · ARC GIS

1 Introduction

It is projected by the United Nations that by 2050, about 80 percent of the world's population would reside in cities. This suggests that a lot of possible calamities will primarily strike in metropolitan areas. After the United Nations International Strategy

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for Disaster Reduction (UNISDR) adopted the Hyogo Framework for Action, the primary focus of disaster risk reduction planning has shifted from merely lowering vulnerability to greatly enhancing and bolstering community resilience. Resilience in this sense is the degree of damage and destruction that a system is capable of withstanding [1, 2]. On the other hand, a crisis is an event that occurs naturally or unexpectedly, imposing problems on human society and disrupting the previously established balance between human needs and available resources. Its resolution requires a series of continuous and dynamic operations and actions known as crisis management [3].The term "earthquake hazard" describes a group of unaffected by human activities natural geophysical circumstances brought about by the shifting, sliding, and displacement of the earth. Given their wide distribution, regularity, and the vast and catastrophic damage they cause, earthquakes—one of the most devastating environmental phenomena—are regarded as one of the most well-known natural catastrophes worldwide [4]. China, Indonesia, Iran, Turkey, and Japan are the five nations most impacted by damaging earthquakes; they account for 16%, 10%, 8%, 4.5%, and 4% of all destructive earthquakes, respectively [5]. Iran is one of the highest-ranking nations in terms of vulnerability to earthquake events and the number of casualties caused by these disasters, as well as ranking first in terms of the frequency of earthquakes with a magnitude greater than 5.5 Richter scale, according to a 2002 report from the United Nations Office for Disaster Risk Reduction (UNISDR). Moreover, Iran is responsible for 6% of global earthquake fatalities and subsequent damages. Remarkably, research by the Ministry of Housing and Urban Development in the National Urban Plan show that half of Iran's urban population lives inin areas with the highest risk of earthquakes. One of the most important factors in reducing earthquake risk is the preparedness of the population to deal with it and increasing urban resilience. One of the best efforts to address the impact of earthquakes, especially in densely populated urban areas, is conducting earthquake risk assessments. Various methods such as seismic data analysis, early warning systems, probabilistic and statistical models, and artificial intelligence have been used to predict earthquake components [4]. However, since humans are involved in the decision-making process, multi-criteria decision-making is accompanied by incompleteness, subjectivity, ambiguity, and other ambiguous qualities. As a solution, numerous studies have combined fuzzy set theory with multi-criteria decision-making methods to reduce these challenges and provide effective and efficient judgments[5]. Regardless, decision-making requires geographical data, which has been a key issue in decision-making since the emergence of multi-criteria decision-making, necessitating the use of geographic information systems [6, 7]. Given the importance of estimating the vulnerability of historical fabrics to earthquake hazards in discussions related to geography and urban planning, this research attempts to provide a suitable estimation of the earthquake vulnerability of Tehran's historical fabrics using ELECTRE FUZZY techniques and Geographic Information System (GIS) by executing spatial and descriptive data and main structural and behavioral elements.

2 Research Method and Case Study

2.1 Research Method

This research has employed a mixed-method approach with practical and developmental objectives to extract results. The overall research process consists of two stages: firstly, data collection, data standardization, weighting using the FAHP method, layer overlay using ArcGIS software, and secondly, prioritization of options using the ELECTRE method. The ELECTRE method is one of the methods available in compensatory models[9]. In this method, all options are evaluated using non-ranking comparisons, and all stages of this process are based on a set of concordant and a set of non-concordant, thus known as a concordance analysis (see Error! Reference source not found.). In this method, options or alternatives are compared in pairs, dominant and inferior options are identified, and inferior or defeated options are eliminated [10].

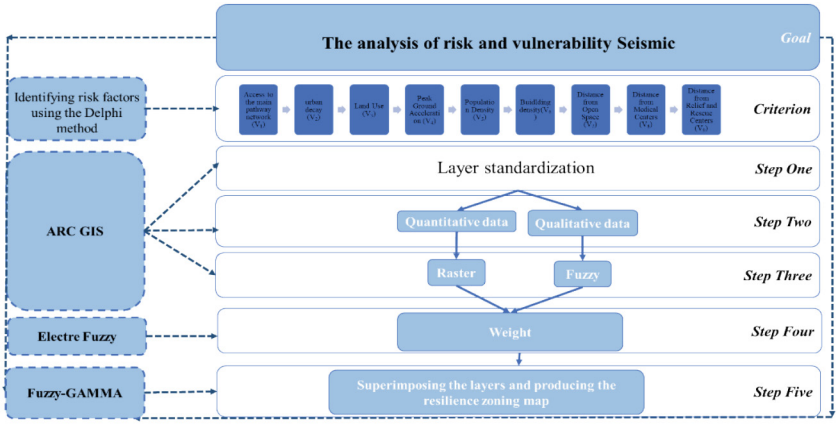

Fig. 1. Research process

2.2 Case Study

The demographic and urbanization landscape of Tehran has undergone significant changes over the past two centuries since its designation as the capital. Presently, the city comprises 22 districts and several associated areas, including cemeteries and southern suburbs [3]. Active faults in Tehran are generally discussed within three main underground zones: northern, central, and southern. The primary zones containing deep faults are capable of generating moderate to severe seismic events in the vicinity and within the metropolitan areas of Tehran and Karaj [11], as well as neighboring settlements [3]. The central and core area of Tehran, including historic neighborhoods such as Emamzade Yahya, Pamenar, Nasir Khusraw, Sangalaj, Bazar, and Sirose (Chaleh Meydan), has been historically and architecturally significant, rich in numerous historical structures, and culturally affluent [12].

3 Discussion and Findings

3.1 First Stage

In the first stage, after data collection, nine research criteria were identified, including access to main road networks, density of deteriorated fabrics, land use, distance from faults, population density, building density, distance from urban open spaces, distance from medical centers, and distance from emergency and rescue centers. Data standardization was performed according to urban regulations and standards, and the criteria were confirmed by experts, as shown in Table 1.

Table 1. Vulnerability ranking assigned for parameters

Ranking	Data type	Fuzzy membership	Consistent	Variables
60–300 m	quantitative	Fuzzy Large	InConsistent	Access to the main pathway network (V_1)
instability -Building quality	qualitative	Fuzzy Large	InConsistent	urban decay (V_2)
Types of land use	qualitative	Fuzzy Small	consistent	Land Use (V_3)
	quantitative	Fuzzy Large	Consistent	Peak Ground Acceleration (V_4)
150–300 m	quantitative	Fuzzy Small	Inconsistent	Population Density (V_5)
Number of floors		Fuzzy Small		Buidlding density(V_6)
1–5 min	qualitative	Fuzzy Small	Consistent	Distance from Open Space (V_7)
1–5 min	qualitative	Fuzzy Small	Consistent	Distance from Medical Centers (V_8)
1–5 min	qualitative	Fuzzy Small	Consistent	Distance from Relief and Rescue Centers (V_9)

After the evaluation criteria were transformed into comparable and standardized scales, the relative weights and importance of each criterion in relation to the research objective were determined using the FAHP method. In addition to Boolean logic and Weighted Overlay tools in ArcGIS 10, two new overlay tools - Fuzzy Membership and Fuzzy Overlay - are available. Overlays using fuzzy logic provide more flexible weighting of evidence and a combination of evidence compared to Boolean or traditional weighted overlays. Furthermore, defining fuzzy numbers and fuzzy scales is necessary for conducting comparisons.

Based on the spatial analysis map (Fig. 2), access to the main road network in the historical fabric of Tehran faces significant challenges due to the predominance of

commercial land use. This area experiences numerous difficulties in terms of access and road network, resulting in slow access and an inadequate network to meet daily needs. Among these challenges, the road network near the Bazar district, due to its commercial nature, increased number of intersections, and narrow roads, has a much worse condition. Considering the high population density in the historical fabric of Tehran during the day, the presence of narrow roads has increased the vulnerability resulting from this parameter to a high to medium level.

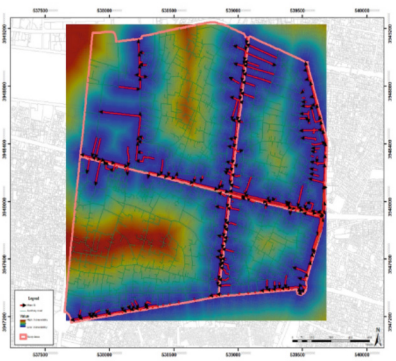

Fig. 2. Analysis of map Access to the main pathway network

Based on the spatial analysis map (Fig. 3), the density of the deteriorated fabric in the historical fabric of Tehran indicates that the vulnerability of deteriorated fabrics and low-quality structures plays a fundamental role in increasing the extent of damage and the spread of crises. Therefore, for this criterion, considering the environmental characteristics of the area, two sub-criteria of instability and granularity have been evaluated. The results of the analysis of the building quality index in this area show that most buildings require repair and are prone to poor quality in the face of earthquakes. Overall, the situation of this parameter falls within the spectrum of high vulnerability, with buildings located in the bazar, Emamzade Yahya, and parts of Siroos neighborhoods having a high density of deteriorated fabric. Meanwhile, the Pamenar neighborhood has a medium vulnerability in terms of building quality.

Based on the spatial analysis map (Fig. 4), the land use in the historical fabric of Tehran indicates that approximately 30% of this fabric is allocated for residential use. A significant portion of these residential areas is located within the deteriorated fabric, which makes this area highly vulnerable due to its resident population. Moreover, the high land value and lucrative nature of commercial uses in this area have led to both legal and illegal changes in land use toward commercial activities. This trend has resulted in most of Tehran's historical fabric being categorized as highly vulnerable in terms of a wide spectrum of vulnerabilities. Based on the spatial analysis map (Fig. 5) of the Peak Ground Acceleration (PGA) in the historical fabric of Tehran, which indicates earthquake hazards, the most threatening faults in this area are the northern and southern Rey faults, the Kahrizak fault, and the northern Tehran fault. These faults show approximately the same level of hazard across the entire area.

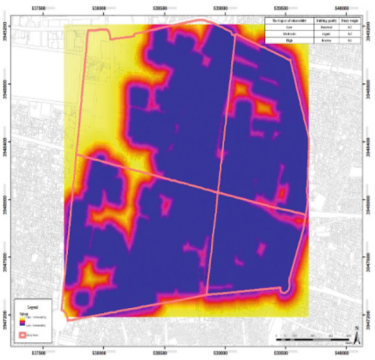

Fig. 3. Analysis of map urban decay

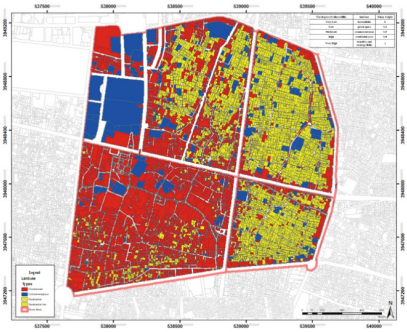

Fig. 4. Analysis of map Land Use

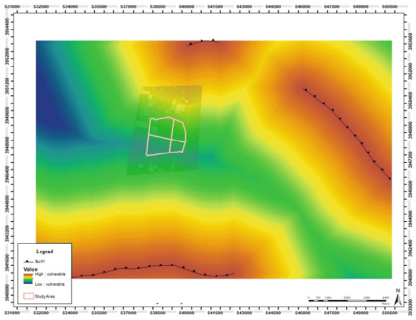

Fig. 5. Analysis of Peak Ground Acceleration

According to the spatial analysis map (Fig. 6) of population density in the historical fabric of Tehran, about 30% of this fabric is designated for residential use, with a significant portion of these areas located within the deteriorated fabric. Due to the high population density in these areas, the human casualties resulting from earthquakes during daytime hours are very high. In this regard, the Bazar neighborhood is highly vulnerable, especially during the late-night hours. Additionally, the high population density in historical areas, coupled with narrow roadways, poses challenges for post-disaster emergency response. Based on the spatial analysis map (Fig. 7) of building density in the historical fabric of Tehran, it is observed that higher-rise buildings increase the risk of road blockages due to building collapse debris, posing challenges for emergency response. Therefore, due to the extensive debris removal required, rescuing residents from multi-story buildings becomes more difficult. Overall, an increase in the number of building floors corresponds to an increase in the vulnerability of buildings to earthquakes. The results indicate that most neighborhoods, including Pamenar, Sirose,

and Emamzade Yahya, have low vulnerability to earthquakes due to their limited building height. However, the Bazar neighborhood is more susceptible to destruction and increased vulnerability due to the presence of multiple high-rise commercial centers.

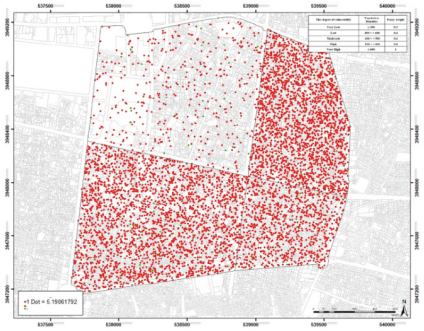

Fig. 6. Analysis of Population Density

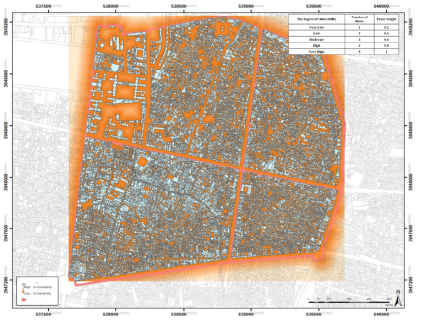

Fig. 7. Analysis of building density

According to the spatial analysis map (Fig. 8) of the distance from public open spaces in the historical fabric of Tehran, the low availability of public open space per capita in this area results in a low to moderate vulnerability of the historical fabric of Tehran in terms of distance from public open spaces. The Bazar and Emamzade Yahya neighborhoods are the most vulnerable residential areas in terms of this parameter. Except for the northern areas with large open spaces, most neighborhoods have very unfavorable conditions in this regard. Based on the spatial analysis map (Fig. 9) of the distance from medical centers in the historical fabric of Tehran, it is evident that this fabric is positioned at varying levels of vulnerability due to the considerable distance from medical centers, ranging from moderate to high vulnerability. Pamenar and the Bazar neighborhoods have the furthest distances from medical centers, resulting in higher vulnerability. Following

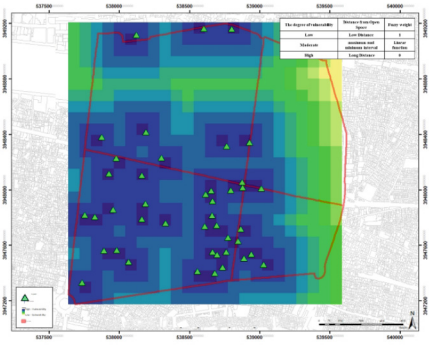

Fig. 8. Analysis of Distance from Open Space

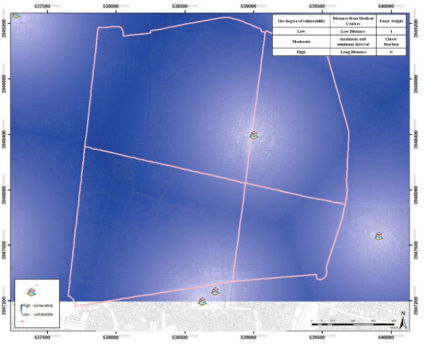

Fig. 9. Analysis of Distance from Medical Centers

these neighborhoods, the Sirose neighborhood is classified as having a moderate level of vulnerability.

According to the spatial analysis map (Fig. 10) of the distance from relief and rescue centers in the historical fabric of Tehran, the distance from these centers plays a crucial role in the speed of response and reducing vulnerability in case of a crisis. The results indicate that all four neighborhoods are classified as having unfavorable to moderate conditions. However, the Bazar neighborhood, due to its sensitivity and the placement of relief and rescue centers, is relatively better positioned in terms of this indicator compared to other neighborhoods.

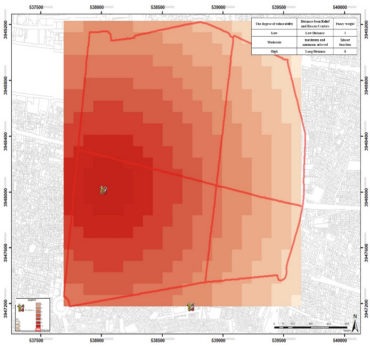

Fig. 10. Analysis of Distance from Relief and Rescue Centers

In this stage of the research, fuzzy gamma (γ) was utilized to estimate the overall vulnerability of Tehran's historical fabric. For this purpose, the data were initially fuzzified. Subsequently, the fuzzy layers were merged together, and a final map was prepared using the Electre fuzzy method to assign weights to the maps, ensuring the impact of each indicator in calculating the actual vulnerability. Maximum and minimum gamma values (0.08, 0.85, 0.9, 0.95) were used to generate the final map using zonal statistics tools for neighborhood fabric calculation [10]. Among these, gamma 0.95 was selected as the best gamma for vulnerability zoning. In the final map (Fig. 11), resilience levels were categorized into three groups based on the intensity of vulnerability: non-resilience, low resilience, and moderate resilience.

3.2 Second Stage

Prioritization of Seismic Risk Using the ELECTRE Method, After overlapping the final layers, four historical and old neighborhoods of Tehran were prioritized in terms of resilience level and seismic risk using the ELECTRE method. Towards the defined objectives, the ELECTRE fuzzy method in this research was conduct-ed in 6 steps using the Electre Solver software: In this study, 4 alternatives (neighborhoods) and 9 criteria were considered, and the manual weighting method along with the use of fuzzy weights from the previous phase was employed for weighting (Tables 2 to 9).

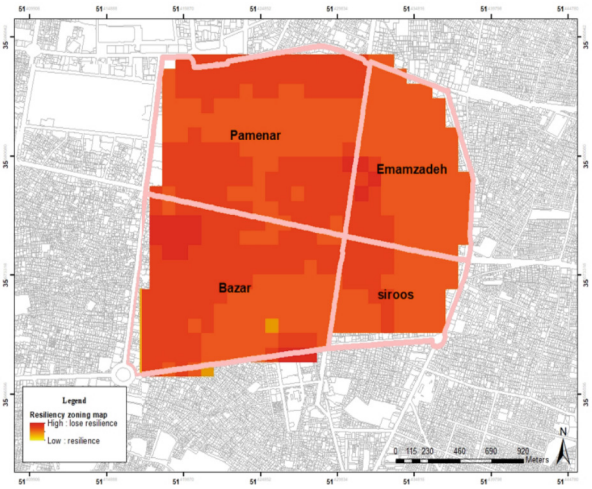

Fig. 11. Resilience zoning map of the historical context of Tehran for an earthquake with 0.95 gamma operator and ELECTRE FUZZY method

Table 2. Decision matrix

Areas	V1	V2	V3	V4	V5	V6	V7	V8	V9
Pamenar	3	4	5	3	3	4	5	1	1
Bazar	5	5	2	3	5	5	3	3	4
Emamzade	4	5	5	3	2	1	2	5	1
Sirose	1	4	2	3	4	3	3	2	2
Weight	0.229	0.192	0.071	0.159	0.026	0.026	0.125	0.008	0.159

Table 3. Descaled decision matrix

Areas	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9
Pamenar	0.213	0.160	0.729	0.560	0.346	0.392	0.656	0.441	0.420
Bazar	0.852	0.480	0.437	0.700	0.577	0.588	0.262	0.55	0.700
Emamzade	0.213	0.800	0.291	0.140	0.577	0.588	0.656	0.55	0.560
Sirose	0.426	0.320	0.437	0.420	0.46	0.392	0.262	0.441	0.140

Dimensionless Scaling of Decision Matrix.

Weighting the Normalized Matrix, In this step, the weights of the criteria obtained in the previous stage are multiplied with the normalized matrix to obtain a weighted matrix.

Table 4. Pairwise comparison matrix of different criteria

Areas	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9
Pamenar	0.048	0.030	0.052	0.089	0.009	0.010	0.082	0.003	0.067
Bazar	0.195	0.092	0.031	0.111	0.015	0.015	0.033	0.004	0.111
Emamzade	0.048	0.154	0.020	0.022	0.015	0.015	0.082	0.004	0.089
Sirose	0.097	0.061	0.031	0.067	0.012	0.010	0.033	0.003	0.022

Table 5. Agreement matrix

Areas	Pamenar	Bazar	Emamzade	Sirose
Pamenar	0.546	0.707	0.192	-
Bazar	0.807	0.928	-	0.807
Emamzade	0.292	-	0.132	0.647
Sirose	-	0.707	0.390	0.488

Table 6. Disagreement matrix

Areas	Pamenar	Bazar	Emamzade	Sirose
Pamenar	1	0.253	1	-
Bazar	0.315	0.071	-	0.420
Emamzade	1	-	1	1
Sirose	-	0.723	1	0.902

Table 7. Formation of the Boolean Concordance Matrix for each of the selected areas

Areas	Pamenar	Bazar	Emamzade	Sirose
Pamenar	0	1	0	-
Bazar	1	1	-	1
Emamzade	0	-	0	1
Sirose	-	1	0	0

Creating a Set of Agreements and Disagreements Contrary to the Criteria, Calculate the Number of dominance and defeat of each of the selected areas.

Table 8. The number of dominance and defeat of each of the selected areas

Result	Number
Bazar	3
Pamenar	1
Sirose	1
Emamzade	0

Table 9. Area of different earthquake vulnerability

Risk potential	Degree of Resilience	Area (square meter)	Area percentage
Very Haigh vulnerability	Loss of Resilience	2692658	78.31%
Haigh vulnerability	Less of Resilience	34384	10%
Moderate vulnerability	Moderate of Resilience	401956	11.69%
Very Low vulnerability	Resilience	-	-
Total area		3438461	100

4 Conclusion

Reducing the vulnerability of Iran's cultural heritage and historical fabric to earthquakes and other natural disasters is one of the country's most significant challenges. In this study, the fuzzy ELECTRE method was utilized to assess the overall vulnerability and resilience of Tehran's historical fabric, integrating it with geographical information systems. The results of the fuzzy ELECTRE calculations indicate that over 78% of Tehran's historical fabric is highly vulnerable, with over 10% at high vulnerability, and over 11% at moderate to low vulnerability to earthquake risk. Additionally, in terms of vulnerability spectra and resilience levels of Tehran's historical neighborhoods, the Bazar neighborhood is classified as highly vulnerable with low resilience, Pamenar and Sirose neighborhoods are categorized as having high vulnerability with low resilience, and the Emamzadeh Yaḥyā neighborhood falls into the moderate to high vulnerability and medium resilience spectrum, prioritizing earthquake vulnerability planning accordingly. Furthermore, among the identified potential earthquake risks, the risk of increased density in the deteriorated fabric, severe lack or shortage of urban open spaces, and high population density ranks highest in earthquake risk for this fabric. Assessing the resilience status of Tehran's historical fabric against potential earthquake crises will play a vital role in crisis management. Due to the existence of a vast area of deteriorated fabric, this area of the city is vulnerable to earthquake hazards. Therefore, determining the vulnerability of the fabric to earthquakes is of utmost importance, both in terms of planning for resilience and emergency management and accommodation.

Disclosure of Interests. The authors have no competing interests. The authors declare that there are no evident financial or personal conflicts of interest that might have affected the results reported in this study.

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