Research Paper: Spatial Assessment of Vulnerability to Earthquake in Rural Settlements Using a Fuzzy Inference System (Case Study: Rural Settlements in the Tehran Metropolitan Area)

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ABSTRACT

Purpose: One of the regions with a high risk of earthquakes in Iran is the Tehran metropolitan area, which includes the provinces of Tehran and Alborz. In recent years, due to population growth, uncoordinated and unprincipled growth, and non-standard construction near the faults, the rural settlements in the Tehran metropolitan area have been more exposed to risk and vulnerability. Therefore, this study aims to spatially assess the potential vulnerability of rural settlements in the Tehran metropolitan area to earthquakes.

Methods: The study population includes all rural settlements located in Tehran and Alborz provinces, which according to the 2016 census, totalled 1519 villages, and among them, 472 villages whose data were available were selected as a sample. Data analysis was performed using a fuzzy inference system (FIS), creating a database of fuzzy rules and combining different indicators in MATLAB software. The output was converted into a map, and its spatial distribution was displayed using ArcMap software.

Results: The findings of the spatial evaluation of population vulnerability indicators, the vulnerability of residential units and earthquake risk indicate the high vulnerability potential of rural settlements to earthquakes. So that the major part of the studied area has a high potential for vulnerability and only limited areas scattered throughout it have a low and medium potential for vulnerability to earthquake risk.

Conclusion: The spatial zoning of the vulnerability of rural settlements to earthquakes in the Tehran metropolitan area has the most similarity with the vulnerability indicator of residential units. As a result, one of the top priorities in this area must be considering retrofitting rural houses.

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1. Introduction

The impact of natural disasters is unequally distributed among communities from different social and physical aspects. According to the Centre for Research on the Epidemiology of Disasters (CRED), disaster victims in developing countries accounted for 69.9% of the world's total damage from natural disasters (Jeong & Yoon, 2018). As population growth continues, especially in developing countries, we expect more people to be at risk of natural disasters (McConnell & Bertolin, 2019) and concentrate more assets in high-risk areas. This means an increasing need for planning to manage or reduce risk, increase adaptability, and reduce vulnerability (Rus et al., 2018; Zhou et al., 2014).

Natural disaster data from the last few decades shows that an average of 60,000 people are killed each year by natural disasters (Global Change Data Lab, 2020). According to the Natural Disaster Epidemiology Research Center (CRED), 389 natural disasters were reported worldwide in 2020, which caused a total of 15080 people to die, 94.4 million people affected, and 171.3 billion US$ in economic damage (CRED, 2021).

Historically, droughts and floods were fatal disaster events. Deaths from these events are now very low, and today's most deadly event is an earthquake. We know from historical data that the world has seen a significant reduction in disaster deaths through earlier prediction, more resilient infrastructure, emergency preparedness, and response systems. But the earthquake is a natural disaster that is still not preventable and affects many people (Global Change Data Lab, 2020). Earthquake is recognized as the most serious disaster and an obstacle to the development of human society (Xu et al., 2020). According to CRED data, earthquakes killed 72,114 people worldwide between 2000 and 2020 and affected 118,344,322 people (Lian et al., 2021).

It is necessary to have a thorough knowledge of the earthquake and an understanding of its potential vulnerability and response capability. Being fully prepared can help mitigate the negative consequences of disasters (Kusumastuti et al., 2021; Basolo et al., 2009; Morrissey, 2007). According to studies, those who are more aware of the dangers of various earthquakes are less affected (Santos-Reyes, 2020; Xu et al., 2018; Kusumastuti et al., 2021; Lian et al., 2021). For this reason, assessing the current situation, gaining sufficient understanding, and analyzing the various dimensions of disasters are essential to presenting vulnerability reduction programs. Vulnerability assessment is a key component of disaster management, especially earthquakes, and it helps to ensure human society's safety (Huq et al., 2020).

Earthquake vulnerability assessment is an important step in planning, preventing, and reducing earthquake vulnerability. A thorough awareness of the potential vulnerability increases a community's preparedness for risk (Birkmann, 2007). Identifying vulnerable people and places is key to assessing potential earthquake vulnerabilities, improving emergency management, and mitigating losses when a natural disaster occurs (Jeong & Yoon 2018; Emrich & Cutter, 2011).

Iran is one of the world's most earthquake-prone countries, with one of the world's ten most deadly earthquakes occurring there (Global Change Data Lab, 2020). Every year, several earthquakes strike Iran, causing different degrees of damage. This problem is magnified in rural settlements of Iran because rural settlements are more vulnerable due to unique characteristics such as low technology, non-resilient buildings, inadequate and non-standard infrastructure, insufficient location, limited access to facilities and services, and a lack of knowledge and awareness (Farajisabokbar et al., 2021).

The Tehran metropolitan area (TMA) is Iran's most populated, accounting for over 20% of the country's total population. Throughout history, this region has been subjected to major earthquakes. Data from paleontological seismology and historical knowledge show a high probability of earthquake occurrence and the potential for large earthquakes in the Tehran metropolitan area (Zare, 2014). The uncoordinated and unprincipled growth of villages in the Tehran metropolitan area, particularly in recent decades, construction near faults and areas prone to geological instability, indicates that serious damage will occur in the case of a large earthquake in this area (Darban Astane et al., 2018). As a response, preparing to minimize vulnerability has become a need. Due to the high risk of earthquakes, earthquake vulnerability assessment in rural settlements of the Tehran metropolitan area is critical. Therefore, this article aims to identify and combine multiple indicators to make an integrated assessment of the potential for earthquake vulnerability in rural settlements in the Tehran metropolitan area. Furthermore, by providing a vulnerability map of rural settlements, this article aims to inform government decision-makers at the national, regional, and local levels about the region's vulnerability.

2. Literature Review

Natural hazards are often referred to as natural disasters, but in reality, that disasters are not natural. Rather, the reactions, non-reactions, or human activities and behaviours that turn natural hazards into natural disasters. For example, who we are, where we live, and how we build our homes are factors influencing the extent to which we are exposed to, and are impacted by, natural hazards (Ogie & Pradhan, 2019). Hazards are events or physical conditions that have the potential to cause fatalities, injuries, property damage, infrastructure damage, interruption of business, socio-economic disruption, environmental damage, or any other type of harm or loss (Michellier et al., 2020; Islam et al., 2013). In other words, natural hazards are recognized as natural-made or natural phenomena that might have negative consequences on society. And may have the potential to cause injury and damage property and the environment (UNISDR, 2015; Shao et al., 2019). Not all natural hazards necessarily lead to natural disasters, but rather exposure to hazards, the presence of vulnerable populations, and human-environmental interactions are ways that lead to a variety of natural disasters (Ma et al., 2020; Chang et al., 2018; Fakhruddin et al., 2019; Huq & Hossain, 2012; Zakour & Swager, 2018).

Disaster risk is a function of a hazard's existence, exposure, and vulnerability (IPCC, 2012). since population growth and asset accumulation increase the possibility of exposure to disaster risk, reducing vulnerability is an important part of risk management or disaster risk reduction (Bouwer et al., 2007; Schumacher & Strobl, 2011). Therefore, a better understanding of the multifaceted nature and different dimensions of vulnerability is a prerequisite for designing and implementing disaster risk management and adaptation strategies (IPCC, 2012).

Vulnerability is often defined as the undesired effect and is the result of various historical, social, economic, political, institutional, and environmental conditions and processes. In the context of disaster risk, vulnerability is defined as a condition determined by physical, social, economic and environmental factors or processes that increase the sensitivity of society to the impact of hazards (UN/ISDR, 2009).

The concept of vulnerability has been applied in various fields and for different spatial levels. It has long been recognized that environmental hazards are the joint product of stress and exposure on the one hand, and fragility and vulnerability, on the other. Although there have been several attempts at defining and capturing what is meant by vulnerability, the use of the term varies among disciplines and research areas (Wei et al., 2004; Aksha et al., 2019). Scientists in the field of social sciences define vulnerability as a set of social, economic and demographic factors that work together to determine people's ability to cope with external factors that cause pressure and stress (Wisner et al., 2004). The interaction between the biophysical environment and social characteristics reveals the state of vulnerability. Finally, vulnerability shows up as unequal impacts on various groups of people across space. As a result, reducing vulnerability requires having sufficient knowledge of the factors affecting vulnerability and a comprehensive understanding of the contexts of these factors (Hewitt, 1997; Cutter et al., 2003; Wisner et al., 2004).

Seismic vulnerability, broadly defined as the potential for loss and the ability to mitigate or respond to earthquake hazards, is an essential concept in hazard research (Cutter, 1996). Seismic vulnerability can be categorized into physical, social, and economic components. In practice, physical vulnerability, particularly that of buildings, was given the greatest attention because most of the deaths or losses in earthquakes have been caused by building collapse (Gao & Ji, 2014). And this is more common in developing countries (Kenny, 2009). Generally, the type of building, materials, and age of the building is considered for earthquake assessment (Porter et al., 2008). However, some social components such as people's age (Kar, 2009; Smith et al., 2009; Phillips & Hewett, 2005) and gender (Enarson et al., 2018) are also important for assessing vulnerability to earthquakes. In general, assessing vulnerability without considering all or most of these components would be inappropriate. As reason, vulnerability assessment should be based on multiple criteria or indications (Yoon, 2012).

According to the topics presented, vulnerability can be divided into two general categories: biophysical and social (Cutter, 1996; Schmidtlein et al., 2008). Biophysical vulnerability expresses the frequency and severity or probability of a hazard (Brooks, 2003). While the social vulnerability is defined as the characteristics of an individual, group or society in terms of their capacity to anticipate, cope, resist and recover from the effects of a natural hazard (Wisner et al., 2004). And finally, the combination of biophysical vulnerability and social vulnerability will lead to the overall vulnerability of a place or spatial area (Zhou et al., 2014). For this reason, understanding the different effects of hazards in different societies requires, on the one hand, knowledge of possible hazards and, on the other hand, knowledge of the capacities of societies to cope and recover (Yoon, 2012).

Although different methods and approaches have been used in recent years in various specialized fields to assess the vulnerability of societies to earthquake hazards, examining this issue in the framework of spatial planning approaches can provide a more integrated and comprehensive understanding. Therefore, the spatial assessment of the vulnerability of different regions is so important to inform and empower governments to adopt policies for planning and distributing relief funds and help regions improve their capabilities against disasters.

Study Area

The study area includes the two provinces of Tehran and Alborz, which are referred to as the Tehran metropolitan area (TMA) in this study. Tehran province (capital of Iran) has an area of about 13842 square kilometres. Tehran province is divided into 16 counties, 46 cities, and 1048 villages. Tehran province in 1976 had a population of 4981349 people, which in 2016 has increased to 13267637 people. In other words, the population of Tehran province has increased 2.66 times over the last 40 years. Alborz province is located in the northwest of Tehran province and covers an area of around 5173 square kilometres. Alborz province comprises 6 counties, 17 cities, and 471 villages. Alborz province was previously known as one of Tehran province's counties, but it was separated from Tehran province in 2011 and became a new province. Alborz province had a population of 2412513 people in 2011, which had increased to 2712400 people in 2016, with a 2.37 per cent annual population growth rate (Statistical Center of Iran, 2019). Combining the two metropolises of Tehran and Karaj in the two provinces described has led to the formation of the Tehran metropolitan area (TMA), which includes 63 urban settlements and 1519 rural settlements. According to the 2016 census, this area (the provinces of Tehran and Alborz) accounts for 20% of Iran's overall population (Statistical Centre of Iran, 2016).

3. Methodology

This research is descriptive and is based on practical research. The research population includes all rural settlements in the TMA, which, according to the 2016 census, equalled to 1519 villages (Statistical Centre of Iran, 2016), with 472 villages having access to their data being selected as a sample in this study based on access to case data and data needs. The required data has been collected from the management and planning organizations of Tehran and Alborz provinces (2016). The criteria used to determine vulnerability in this article are based on a survey of theoretical literature and research background, and their scientific validity has also been confirmed. Finally, according to the availability of data, a total of 7 main indicators were determined, including the ratio of buildings with resistant materials, the ratio of buildings with non-resistant materials, residential units area, population density per residential unit, the ratio of the vulnerable population, sex ratio, and earthquake risk (Table 1).

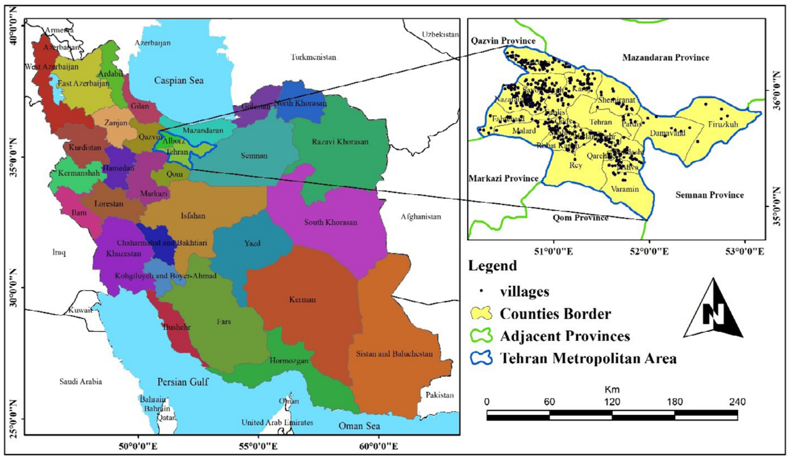

Figure 1. Map of Tehran metropolitan area (TMA)

Table 1. Indicators used to assess the vulnerability of rural settlements to earthquakes

Indicator		Description
The ratio of buildings with resistant materials		The proportion of buildings with metal and concrete materials to the total number of village buildings multiplied by 100.
The ratio of buildings with non-resistant materials		The proportion of buildings with brick and iron, brick and wood, cement block, all brick or stone and brick, all wood, clay and wood, and clay and mud materials to the total number of village buildings multiplied by 100.
Residential units area	≤ 100 m2	The proportion of residential units with an area of 100 square meters and less than the total number of village residential units multiplied by 100.
	101 to 200 m2	The proportion of residential units with 101 to 200 square meters to the total number of village residential units multiplied by 100.
	> 200 m2	The proportion of residential units with an area of more than 200 square meters to the total number of village residential units multiplied by 100.
Population density per residential unit		The proportion of the population to the number of residential units (person/residential unit).
The ratio of vulnerable population		The proportion of the number of people under 15 and over 65 to the total population multiplied by 100.
Sex ratio		The proportion of the male population to the female population multiplied by 100.
Earthquake risk		The study area (TMA) includes moderate, high, and very high risk.

Source: Ahmed & Kelman, 2018; Huq et al., 2020; Santos-Reyes, 2020; Alam & Haque 2021; Li et al., 2020; Peng, 2015; Yoon, 2012; Tsai & Chen, 2010; Tian et al., 2015; Berman et al., 2015; Jeong & Yoon, 2018; Gao et al., 2014; Aksha et al., 2019; Fraser et al., 2021; Munyai et al., 2021

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Source: Data related to residential units and the population of the studied villages (Indicators 1 to 6 in Table 1) have been collected from the 2016 statistics of the Management and Planning Organization of Tehran and Alborz provinces. Also, the earthquake risk indicator (Indicator 7 in Table 1) is based on the zoning of earthquake risk in Iran according to standard 2800 (version 4) of the Iran Ministry of Roads & Urban Development in 2014. Then the fuzzy inference system (FIS) was used in the MATLAB software. The vulnerability was assessed for each indicator by creating a fuzzy rules database. The definition of the rules was based on the opinions of experts. The fuzzy rules database is defined in 4 stages (each stage defining 27 rules) to complete this process and determine the overall vulnerability (a total of 108 rules) for the studied Rural settlements. ArcMap software was used to visualize the spatial distribution of the outputs after assessing the degree of potential vulnerability (Figure 2).

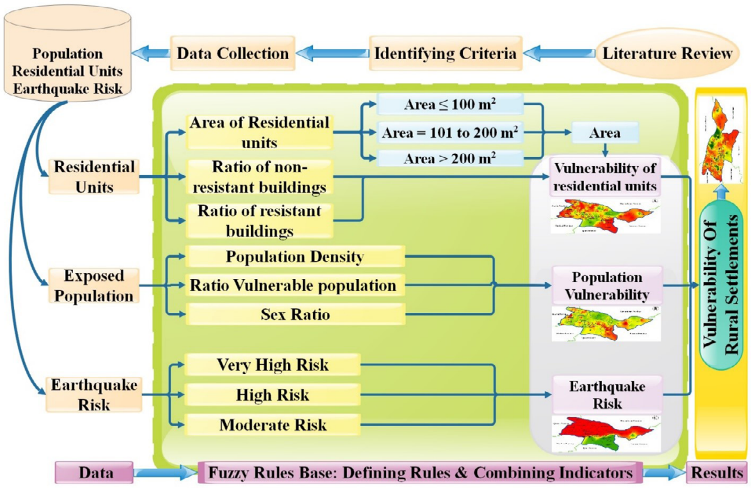

Figure 2. research process models

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3.1. Fuzzy inference system

A fuzzy inference system is a rule-based system consisting of three components: (A) a rule base that contains a set of fuzzy if-then rules. (B) A database that defines the membership functions of the input-output variables used in fuzzy rules, and (C) a reasoning mechanism that combines these rules into a mapping routine from the system's inputs to outputs, to derive a reasonable output conclusion (Nayak et al., 2005). While the input variables can be presented to the FIS either as crisp values or fuzzy sets, the output from a FIS is generally a fuzzy set. The IF-THEN rules in the FIS facilitate a nonlinear mapping between the input and output space of the system being modelled. The fuzzy rules split the total input-output space into several local regions, and each rule represents the local behaviour of the nonlinear mapping. Therefore, the efficacy of the FIS is largely dependent on the number of fuzzy rules. It is to note that while the efficacy of the FIS increases with the increase in the number of rules as the inference space increases with rules, formulating a high number of rules is a tedious task (Vema et al., 2019).

There are two approaches in the FIS development: (A) the Mamdani approach (Mamdani & Assilian, 1975) and (B) the Takagi-Sugeno approach (Takagi & Sugeno, 1985). In this research, the Mamdani approach is used. There are three clear procedures for the Mamdani approach, i.e. fuzzification of the input variables, logic decision, and defuzzification of the FIS output (Nayak et al., 2005). Both linguistic variables and observed data can be used to create a Mamdani fuzzy model (Mahapatra et al., 2011). This model uses many rules for system modelling (Tiri et al., 2018). In this method, membership functions of vulnerability determinants and fuzzy rules are defined, and then the MATLAB package fuzzy logic toolbox (R2019a) is used to achieve the output.

To combine the indicators and assess potential vulnerability, a FIS was used. The model framework was created first. Then, the number of system inputs and outputs, the fuzzy inference type, and fuzzy membership functions were defined for each variable. The membership functions used in this study are all trimf-type membership functions because of the nature and applicability of the variables. So the variables were defined using linguistic terms and classified into three categories based on the range of data changes: low, moderate, and high. Accordingly, in step (1), membership functions were defined for the building area indicator, in which the potential vulnerabilities of residential units with an area of 100 square meters and less, residential units of 101 to 200 square meters, and residential units of more than 200 square meters were determined at three low, moderate and high levels. In step (2), the output of the previous step was combined with two indicators, including; the ratio of buildings with resistant materials and the ratio of buildings with non-resistant materials. The membership functions were defined, and the potential vulnerability of residential units was determined at three levels: low, moderate, and high. In step (3), population indicators such as population density per residential unit, the ratio of the vulnerable population, and the sex ratio were combined. The membership functions were defined, and the potential vulnerability based on population indicators was determined at three levels: low, moderate, and high. In step (4), the outputs of steps 2 and 3 were combined with the earthquake risk indicators, the membership functions were defined as in the previous steps, and finally, the amount of potential vulnerability was determined for each of the rural settlements in the Tehran metropolitan area (TMA).

Step (1):

$$f(Area \leq 100m2) = \begin{Bmatrix} low: x < 30 \\ med: \leq 30\ x \leq 60 \\ high: x > 60 \end{Bmatrix}$$

$$f(Area101\ to\ 200m2) = \begin{Bmatrix} low: x < 20 \\ med: \leq 20\ x \leq 30 \\ high: x > 30 \end{Bmatrix}$$

$$f(Area > 200m2) = \begin{Bmatrix} low: x < 10 \\ med: \leq 10\ x \leq 15 \\ high: x > 15 \end{Bmatrix}$$

Step (2):

$$f(Resistant\ buildings) = \begin{Bmatrix} high: x < 30 \\ med: \leq 30\ x \leq 50 \\ low: x > 50 \end{Bmatrix}$$

$$f(NonResistant\ buildings) = \begin{Bmatrix} low: x < 30 \\ med: \leq 30\ x \leq 50 \\ high: x > 50 \end{Bmatrix}$$

$$f(Area) = \begin{Bmatrix} low: x < 50 \\ med: \leq 50\ x \leq 70 \\ high: x > 70 \end{Bmatrix}$$

Step (3):

$$f(Population\ density) = \begin{Bmatrix} low: x < 3{,}5 \\ med: \leq 3{,}5\ x \leq 4 \\ high: x > 4 \end{Bmatrix}$$

$$f(Vulnerable\ population) = \begin{Bmatrix} low: x < 27 \\ med: \leq 27\ x \leq 31 \\ high: x > 31 \end{Bmatrix}$$

$$f(Sex\ Ratio) = \begin{Bmatrix} high: x < 100 \\ med: \leq 100\ x \leq 110 \\ low: x > 110 \end{Bmatrix}$$

Step:(4)

$$f(Vulnerability\ of\ residential\ units) = \begin{Bmatrix} low: x < 40 \\ med: \leq 40\ x \leq 70 \\ high: x > 70 \end{Bmatrix}$$

$$f(Population\ vulnerability) = \begin{Bmatrix} low: x < 30 \\ med: \leq 30\ x \leq 40 \\ high: x > 40 \end{Bmatrix}$$

$$f(Earthquake\ Risk) = \begin{Bmatrix} low: x < 1 \\ med: \leq 1\ x \leq 2 \\ high: x > 2 \end{Bmatrix}$$

4. Findings

The earthquake risk zoning map based on the Iran Ministry of Roads & Urban Development zoning (standard 2800) was investigated first. Based on this zoning, Iran's entire country is divided into four different seismic risk zones: low, moderate, high, and very high-risk zones. And also, the Tehran metropolitan area (TMA) is located in three zones moderate risk, high risk, and very high risk. The majority of TMA's territory is in a high-risk zone. According to a TMA earthquake risk survey, 494 square kilometres, or 2.63 per cent of the whole area, are in a moderate risk zone, 4966 square kilometres, or 26.39 percent of the whole area, are in a high-risk zone, and 13356 square kilometres, or 70.98 per cent of the whole area, are in a very high-risk zone (Table 2).

According to the examined factors, none of the rural settlements is in a moderate earthquake risk zone, and most of them are in a very high earthquake risk zone. So, 75.2% of the total population and vulnerable population of the investigated rural settlements live in the zone with very high earthquake risk. 77.1% of total residential units are located in a very high earthquake-risk zone. Furthermore, 77.6% of buildings with resistant materials, 76.2% of buildings with non-resistant materials, 77.1% of residential units with an area of 100 square meters or less, 76.9% of residential units with an area of 101 to 200 square meters, and 77.1% of residential units with an area of 200 square meters or more are in a very high earthquake risk zone. According to the average of the eight variables investigated, 23.5% of TMA rural settlements are in the high earthquake risk zone, and 76.5% are in the very high earthquake risk zone. These statistics show very high risk, an unfavourable condition, and a high potential for vulnerability to earthquakes in rural settlements located in TMA.

According to housing and population statistics in the studied villages, there are a total of 236231 residential units in 472 sample rural settlements, with a total population of 828179 people. This statistic is different among the villages located in TMA. Some villages are smaller, with fewer residential units and a lower population, while others are bigger, with more residential units and a larger population. The spatial distribution of the number of rural residential units in the region shows that rural settlements with a high number of residential units are often located in the south and southwest of the TMA. Also, the spatial distribution of the total population of rural settlements indicates a greater concentration of population in the south, southwest, and to some extent, the west of the region. Although the density of villages in the TMA west and northwest seems to be high, most of them are settlements with a small number of residential units (250 and less) and a lower population (500 people and less). But most of the rural settlements located in the south of TMA are in the group of villages with a high number of residential units (750 residential units and more) and a larger population (more than 1000 people) (Figure 3).

The total number of residential units is 236231, which means 149751 units represent 63.5 per cent of total residential units built with resistant materials and 85855 units represent 36.5 per cent of total residential units built with non-resistant materials. In different settlements throughout the TMA, the ratio of resistant to non-resistant units is different. According to the spatial distribution of rural settlements based on building resilience, some villages in the TMA south and southwest, including the counties of Eslamshahr, Robat Karim, Baharestan, Shahriar, and Rey, as well as some counties in the north of the TMA, including Shemiranat and Pardis, have a high proportion of resistant buildings and a low proportion of non-resistant buildings. In addition, some villages in the south of the TMA, such as some villages located in Varamin, Pakdasht, Pishva, and Qarchak, as well as some areas in the west of the TMA, such as some villages located in Savojbolagh, Eshtehard, Nazarabad, and Taleqan counties, have a high proportion of non-resistant buildings and a low proportion of resistant buildings (Figure 4).

Table 2. Earthquake risk zoning in the TMA

Risk level	Area (Km2)	Per cent	Cumulative per cent
Moderate	494	2.63	2.63
High	4966	26.39	29.02
Very high	13356	70.98	97.37
Total	18816	100	100

Source: Iran Ministry of Roads & Urban Development, 2014

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Table 3. Research variables based on earthquake risk

Variables	Earthquake risk							
	Moderate		High		Very high		Total	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Total population	0	0	205787	24.8	622392	75.2	828179	100
Vulnerable population	0	0	61124	24.8	185680	75.2	246804	100
Total residential units	0	0	54121	22.9	182110	77.1	236231	100
Buildings with resistant materials	0	0	33513	22.4	116238	77.6	149751	100
Buildings with non-resistant materials	0	0	20470	23.8	65385	76.2	85855	100
Residential units with an area ≤ 100 m2	0	0	45088	22.9	152189	77.1	197277	100
Residential units with an area 101 to 200 m2	0	0	8089	23.1	26907	76.9	34996	100
Residential units with an area > 200 m2	0	0	697	23.0	2331	77.0	3028	100
Average	-	0	-	23.5	-	76.5	-	100

Source: ???

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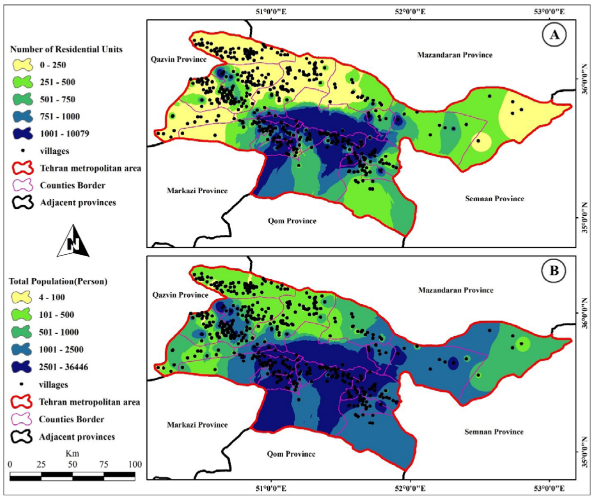

Figure 3. Spatial distribution of the total number of residential units (A) and the total number of rural settlements population (B) in the TMA

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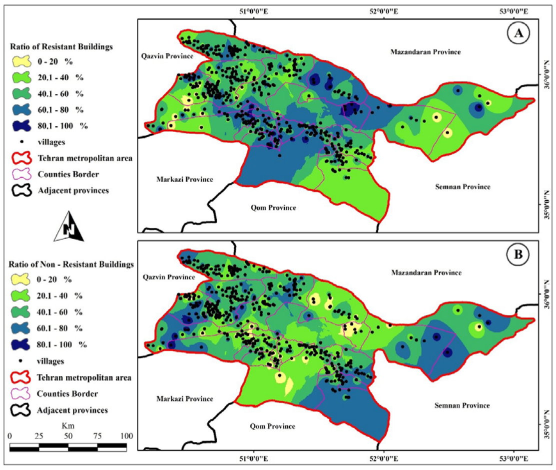

Figure 4. Spatial distribution of; the ratio of rural buildings with resistant materials (A) and the ratio of rural buildings with non-resistant materials (B) in the TMA

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The study of residential units in the villages of the TMA based on the area shows that among the total residential units, 197277 units, or about 83.5 percent of all residential units, have an area of 100 square meters or less, and 34996 units, or about 14.8 percent of all units, have an area of 100 to 200 square meters. 3028 units, or about 1.3 percent of all units, are larger than 200 square meters. Furthermore, 930 units, or roughly 0.4 percent of total residential units, are recorded in the statistics as unrecognized. As a result, the majority of rural residential units in the TMA have a small area, making them more vulnerable to earthquakes. The spatial distribution of rural settlements based on the area of residential units also confirms the high proportion of residential units with an area of 100 square meters or less in the region (Figure 5).

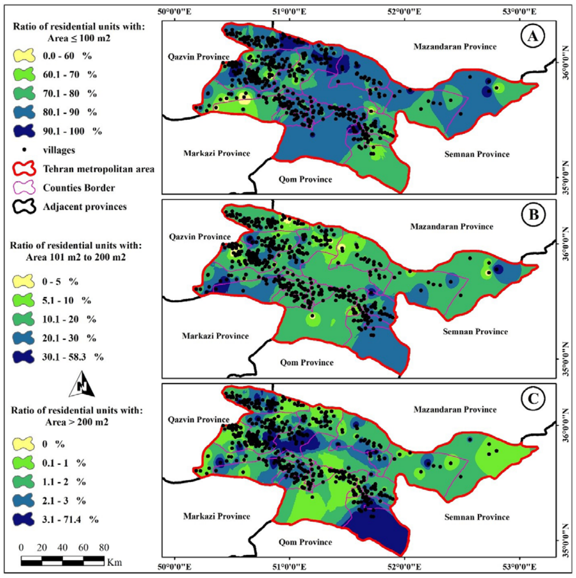

Figure 5. The spatial distribution ratio of rural residential units with an area of 100 square meters and less (A), the ratio of rural residential units with an area of 101 to 200 square meters (B), and the ratio of rural residential units with an area of more than 200 square meters (C) in TMA

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The study of population variables in the studied rural settlements indicates that the average population density is 3.5 people per residential unit. Based on the ratio of the vulnerable population, 246804 people out of the total population (828179) of the studied rural settlements, and about 29.8% of them are a vulnerable population. Based on the sex ratio variable, 433,951 people out of the total population are men, and 394,228 are women, so the sex ratio is 110. Also, the spatial distribution of population indicators shows that the population density index in villages located in the south of the TMA and some villages in the form of small and scattered spots located in the west, north, and east of the TMA have a higher density and other villages have a lower population density in residential units. In terms of the vulnerable population index, the spatial distribution in the villages is relatively balanced, with a vulnerable population ratio of between 25 and 35 percent in the majority of villages. The spatial distribution of the sex ratio index is such that some villages in the north and northwest of the TMA, which correspond to a small part of Shemiranat and Taleqan Counties, have a lower sex ratio, and some small and large areas distributed throughout the TMA have a greater sex ratio (Figure 6).

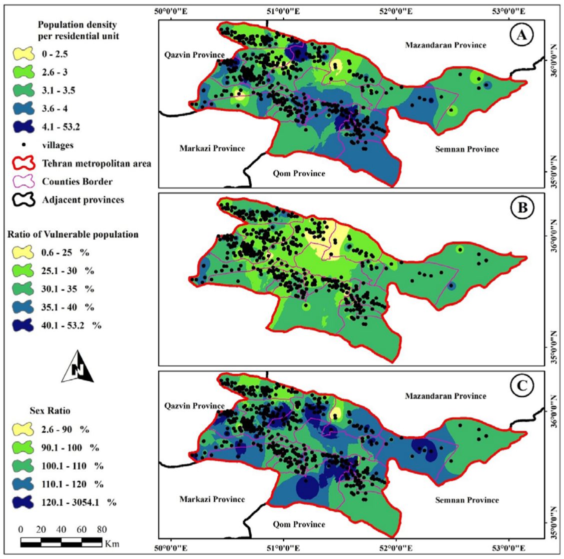

Figure 6. Spatial distribution of population density in rural residential units (A), the ratio of a vulnerable population (B), and the sex ratio (C) in the TMA

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By combining the indicators using a fuzzy inference system, the potential vulnerability of rural settlements in the metropolitan area of Tehran was obtained. The potential vulnerability of residential units was determined in this step by combining three indicators: (1) the ratio of buildings with resistant materials, (2) the ratio of buildings with non-resistant materials, and (3) potential vulnerability due to the area of residential units (less than 100 m², 101 to 200 m², and more than 200 m²). The level of vulnerability in TMA rural settlements ranges from 11.48 (low) to 69.76 (high). Based on this output, as shown in Figure 7-A, the small zone in the centre of the TMA has low and moderate potential vulnerabilities, and wider zones in the west, south, and east of the TMA have high potential vulnerabilities. In the next step, by combining three population-related indicators, including: (1) population density per residential unit, (2) the ratio of the vulnerable population, and (3) sex ratio, the potential vulnerability of the population at risk was discovered. The vulnerability of the population ranges from 9.74 (low) to 71.86 (high) in the TMA rural settlements. As shown in Figure 7-B, one zone in the south of the TMA and small zones in the east and west of the TMA has high vulnerabilities, while wider zones of the TMA have mainly low and moderate vulnerabilities. Also, as previously mentioned, the TMA is classified as moderate risk, high risk, and very high risk according to the earthquake risk index. Most of the TMA is located in a high-risk zone (Figure 7-C).

The final value of the potential vulnerability index for each of the analyzed rural settlements in the TMA was calculated by combining three key research indicators, including the population vulnerability index, residential unit vulnerability index, and earthquake risk. The spatial distribution of the vulnerability index ranges from 11.64 (low vulnerability) to 74.09 (high vulnerability) among the studied rural settlements. According to the developed spatial model, as shown in Figure 8, a major portion of the TMA is vulnerable to earthquake risk. Only a few areas in the north, south, west, and east of TMA rural settlements have a low and moderate vulnerability to earthquakes.

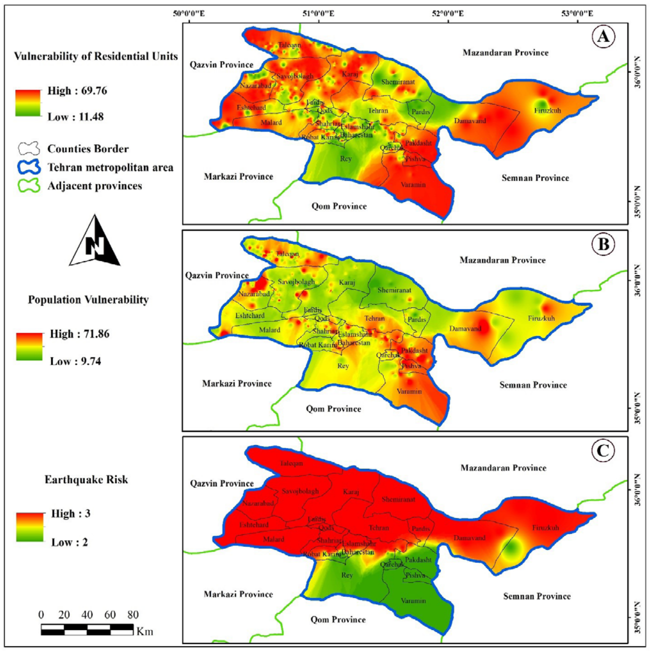

Figure 7. Spatial distribution of vulnerability of rural residential units (A), the vulnerability of rural population (B), and earthquake risk (C) in the TMA.

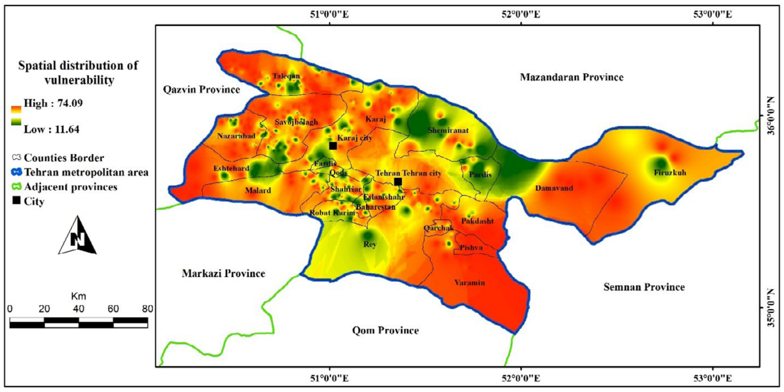

Figure 8. Spatial distribution of rural settlements vulnerability to earthquakes in the TMA

5. Discussion

Earthquakes are among the most dangerous natural hazards, resulting in significant loss of life and property in communities. Iran is known for being one of the most earthquake-prone countries in the world, with many earthquakes occurring each year, some of which have caused significant damage. In addition, the TMA, which is surrounded on four sides by many faults, is one of the regions in Iran with considerable earthquake risk. And throughout history, this region has experienced great earthquakes. The high risk of earthquakes in this region, on the one hand, and the high population density and high density of residential units in this region, on the other, have always raised concerns about the vulnerability of cities and villages in this region to possible earthquakes. The TMA alone accounts for 20% of Iran's total population, and this issue has increased attention to the TMA's vulnerability to earthquake risk. So far, researchers have studied the vulnerability of cities in the TMA (there are 63 cities in this area), but the vulnerability of rural settlements in the TMA has gotten little attention. Perhaps researchers have forgotten this issue in the field of risks and natural disasters due to the important political and administrative positions of the two metropolises of Tehran and Karaj. Due to the importance of the subject, this study has evaluated the potential vulnerability of rural settlements to earthquake risk in the TMA.

The concept of earthquake vulnerability is multi-dimensional and multi-faceted, and various factors influence it. It is not possible to assess the potential vulnerability to earthquakes solely based on earthquake risk or distance from faults; other variables such as the population exposed to earthquake risk, the resistance of residential units, population density, compactness of rural settlements, access to health services, the age structure of the population, the vulnerable population, the sexual composition of the population, and so on are all necessary to assess the potential vulnerability to earthquakes. For this reason, in the present study, an attempt has been made to use a variety of variables that could have access to the data to assess vulnerability to earthquake risk. Combining different variables and indicators to evaluate a particular concept is difficult and requires specific consideration. Although several methods for combining indicators and assessing various concepts have been developed, methods based on fuzzy logic have good capability. To combine different variables and indicators in this study, the base model of the fuzzy inference system in the framework of fuzzy logic was applied. The fuzzy inference system can allow expert knowledge to be used in the definition of rules and the combination of indicators. It also can facilitate the complex process of defining, combining, and evaluating variables and indicators for the researcher through linguistic terms.

The study results show that most of the rural settlements in the TMA are located in the zone with very high earthquake risk, and in the high-risk zone, there are only a limited number of rural settlements, and in the zone with moderate earthquake risk, there are no rural settlements. This condition is considered one of the most important reasons for increasing the potential vulnerability to a possible earthquake. The results revealed that most of the rural settlements investigated have high levels of vulnerability in terms of population indicators, residential unit-related indicators, and earthquake risk. If these indicators were evaluated individually, the importance of this issue and the vulnerability level might not be as visible. For example, when the indicators related to the vulnerability of the population are examined and evaluated alone, the results do not appear to be particularly alarming or out of the ordinary. However, when these indicators are combined with the earthquake risk and vulnerability indicators of residential units, the output is quite alarming. And most of the rural settlements in the TMA have a high potential for vulnerability to possible earthquakes. Also, the spatial zoning and the final output of the vulnerability of rural settlements in the Tehran metropolitan area are the most consistent and similar to the spatial zoning of the vulnerability indicator of residential units.

In conclusion, various strategies in residential unit resilience, educational actions, health interventions, and macro-policy measures to mitigate vulnerability are necessary for the planning purposes of rural settlements in the TMA. In the field of housing, establishing special requirements for the reconstruction and rehabilitation of rural housing, creating detailed guidelines and regulations for the use of resistant materials (metal and concrete) in the construction of new rural housing units, making loans and grants available for the repair and restoration of non-resistant rural structures, and establishing expertise monitoring at various stages of the residential unit construction process are required. Other effective and feasible measures taken by the planners of Tehran and Alborz provinces include equipping medical service facilities and medical emergencies, increasing the readiness of crisis management centres to deal with earthquakes, increasing educational services, and giving appropriate information to residents to increase their knowledge and skills about the earthquake and the possible damage it may cause as well as how to respond to it. It is also suggested that long-term strategies be established at the national level to minimize migration from other Iranian provinces to the TMA to prevent population increase and decrease population density in TMA rural settlements.

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Conflict of Interest

The authors declared no conflicts of interest.

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