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Analysis of the vulnerability of rural settlements to earthquakes in TMA using fuzzy inference system and spatial statistics techniques

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Abstract

The Tehran metropolitan area, encompassing Tehran and Alborz provinces in Iran, is characterized by a high risk of earthquakes due to multiple active faults and a dense population. The uncoordinated and unprincipled growth of rural settlements in this region, coupled with non-standard construction near fault lines, poses a significant potential for vulnerability to earthquakes. This research paper aims to spatially assess the vulnerability of rural settlements located in the Tehran metropolitan area to earthquakes by analyzing factors such as earthquake risk, population density, and building types. The study encompasses the entire rural settlements situated in Tehran and Alborz provinces. Based on the 2016 census, the total number of such villages was reported to be 1519. From this population, a sample of 472 villages for which data were available was selected to serve as representative units for analysis. To analyze the data, a fuzzy inference system (FIS) was employed. This involved the construction of a database comprising fuzzy rules and the integration of diverse indicators within MATLAB software. The resulting output was subjected to analysis utilizing spatial statistics techniques. This study shows the high potential for the vulnerability of rural settlements located in the Tehran metropolitan area to earthquakes.

1. Introduction

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 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 2004). 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).

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

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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, this article aims to providing a vulnerability map of rural settlements in the Tehran metropolitan area.

2. Method

This research is descriptive in nature and is based on practical research. The research population includes all rural settlements in the TMA, which, according to the 2016 census, equaled 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 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 1) ratio of buildings with resistant materials, 2) ratio of buildings with non-resistant materials, 3) residential units' area, 4) population density per residential unit, 5) the ratio of vulnerable population, 6) sex ratio, and 7) earthquake risk.

Data related to residential units and the population of the studied villages have been collected from the 2016 statistics of general population and housing census of Iran (Statistical Centre of Iran, 2016). Also, the earthquake risk indicator is based on the zoning of earthquake risk in Iran according to the standard 2800 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 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, and performing spatial analysis of vulnerability

2.1. Study Area

The study area is two provinces of Iran including Tehran and Alborz provinces, which are referred to as the Tehran metropolitan area (TMA) in this study. Tehran province has an area of about 13842 square kilometers. Tehran province is divided into 16 counties, 46 cities, and 1048 villages. Tehran province has a population of 13267637 people. 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 has a population of 2,712,400 people (Figure 1).

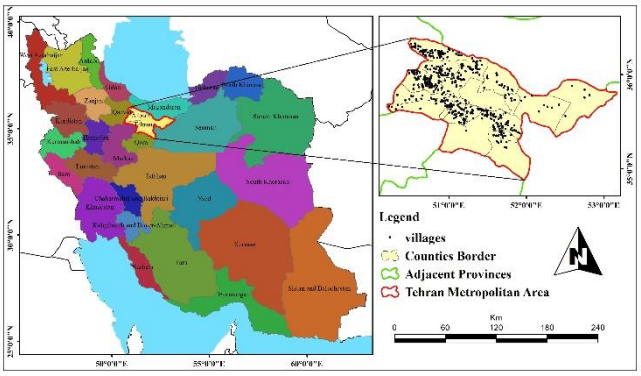

Figure 1. Map of the study area (TMA)

3. Results

According to a TMA earthquake risk survey, 494 square kilometers, or 2.63 percent of the whole area, are in a moderate risk zone, 4966 square kilometers, or 26.39 percent of the whole area, are in a high-risk zone, and 13356 square kilometers, or 70.98 percent of the whole area, are in a very high-risk zone "Table 1".

Table 1. Earthquake risk zoning in the TMA

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

According to the examined factors, none of the rural settlements are 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 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 unfavorable condition, and a high potential for vulnerability to earthquakes in rural settlements located in TMA.

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 m^2, 101 to 200 m^2, and more than 200 m^2). 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 2-A, the small zone in the

center of the TMA have 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 2-B, one zone in the south of the TMA and small zones in the east and west of the TMA have 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 2-C).

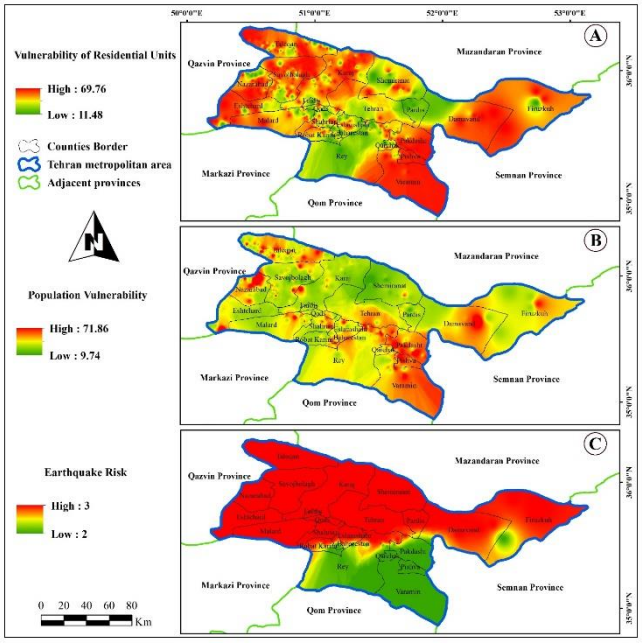

Figure 2. Spatial distribution of vulnerability of rural residential units (A), the vulnerability of rural population (B), and earthquake risk (C) in the TMA

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 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 3.

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.

In order to determine the cluster or randomness of the spatial pattern of the vulnerability of rural settlements located in the Tehran metropolitan area, spatial autocorrelation analysis (Morans I) has been used. According to the results of the spatial autocorrelation test conducted on the vulnerability data of rural settlements, it has been found that there exists a cluster spatial pattern at the level of the Tehran metropolitan area. The value of Moran's index for the vulnerability of rural settlements is 0.053, and since this value is greater than zero, it indicates the presence of a cluster spatial pattern. Furthermore, the Z value is calculated to be 3.58, with a corresponding P-value of zero. This confirms the existence of a cluster spatial pattern with a confidence level of 99%. As depicted in Figure 4, the spatial cluster pattern can be observed through the placement of the standard Z scores on the right side of the normal distribution, highlighted in red.

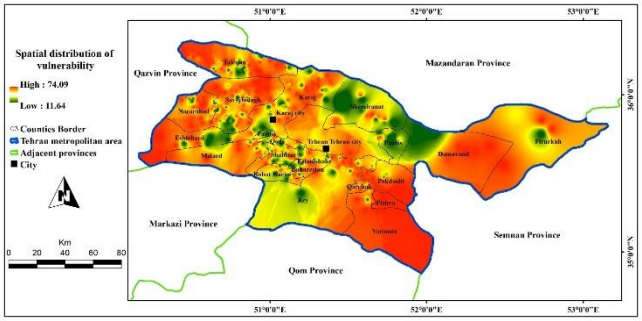

Figure 3. Spatial distribution of rural settlements vulnerability to earthquakes in the TMA

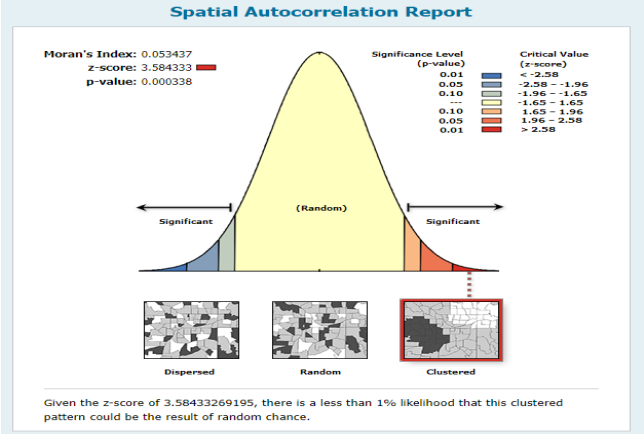

Figure 4. Spatial autocorrelation test for the vulnerability of rural settlements

The application of Hot Spot analysis has facilitated the identification of spatial areas exhibiting concentrated clusters with high and low values, displaying spatial correlation. The outcomes of the hot spot analysis conducted on the vulnerability of rural settlements demonstrate the existence of two hot clusters in the southeast and northwest regions of the Tehran metropolitan area. Furthermore, two cold clusters have formed in the southwest and northeast areas of Tehran city (Figure 5).

4. Conclusion

Earthquakes pose a grave threat to communities, leading to substantial loss of life and property. Iran is renowned for being one of the most earthquake-prone countries globally, experiencing frequent seismic activity with some instances causing significant devastation. Notably, the Tehran metropolitan area (TMA), encompassed by multiple fault lines, stands as a region in

Iran with a considerable risk of earthquakes. Throughout history, this area has witnessed major seismic events. The conjunction of high earthquake risk and the dense population and concentrated residential units in the TMA raises concerns regarding the vulnerability of cities and villages to potential earthquakes.

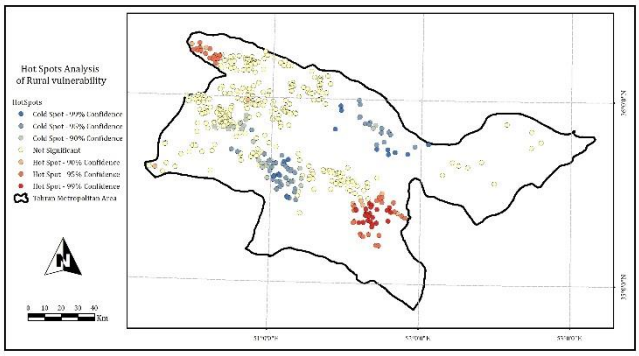

Figure 5. Hot and cold clusters of vulnerability of rural settlements

The TMA, with its substantial population, accounting for 20% of Iran's total, has drawn increased attention to the vulnerability of this region to earthquake risks. While previous research has primarily focused on evaluating the vulnerability of cities within the TMA, consisting of 63 cities, limited attention has been given to the vulnerability of rural settlements. It is plausible that researchers may have overlooked this aspect concerning natural disaster risks, potentially due to the notable political and administrative significance associated with the metropolises of Tehran and Karaj. The study findings indicate that the majority of rural settlements within the Tehran metropolitan area (TMA) are situated in zones characterized by a very high risk of earthquakes. Conversely, only a limited number of rural settlements are located in high-risk zones, and no rural settlements are found in zones with moderate earthquake risk. This condition is considered one of the primary reasons contributing to the increased potential vulnerability in the event of an earthquake.

The results further reveal that most of the investigated rural settlements exhibit high levels of vulnerability across population indicators, indicators related to residential units, and earthquake risk. When these indicators are evaluated individually, the importance of this issue and the level of vulnerability may not be readily apparent. For instance, when solely examining and evaluating indicators related to population vulnerability, the results may not appear particularly alarming or extraordinary. However, when these indicators are combined with earthquake risk and indicators of vulnerability pertaining to residential units, the overall picture becomes considerably more alarming. As a result, a significant number of rural settlements in the TMA have a high potential for vulnerability in the face of possible earthquakes.

In summary, effective strategies are necessary for the planning and resilience of rural settlements in the Tehran metropolitan area (TMA). These strategies should encompass residential unit resilience, education, health interventions, and macro-policy measures. Key measures include establishing requirements and guidelines for housing reconstruction, promoting the use of resistant materials, providing financial support for repairs, and implementing expert monitoring. Equipping medical facilities, enhancing crisis management centers, expanding educational services, and raising awareness among residents about earthquakes are also crucial.

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