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Evaluating Multi-Hazard Preparedness for a Major Earthquake: A Case Study of Tabriz City (NW Iran)

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Abstract

Tabriz, a key economic and political hub in Iran, is highly susceptible to a range of natural hazards, particularly earthquakes and landslides. This study develops a multi-hazard risk scenario – combining earthquake, triggered landslides, and their cascading impacts on road transportation – to assess the potential impact of a 7.3 magnitude earthquake on the city's infrastructure and emergency response systems. Using a GIS-based hazard model integrated with demographic and structural data, we analysed the impacts of earthquakes and landslides on road accessibility, mortality rates, and the effectiveness of disaster relief efforts. The findings reveal that Tabriz's emergency response capabilities and main roads, particularly in the northern districts, would be critically impacted by both the earthquake and subsequent landslides, resulting in significant delays in rescue operations and a high loss of life. Up to 30% of the city's buildings are at risk of collapse, with the most vulnerable populations — including children, women, and low-income communities—facing the greatest risk. The projected death toll could reach 17%, with casualties rising further if emergency response is delayed. Moreover, areas previously considered relatively safe from seismic risks may still suffer substantial damage due to landslides. This study underscores the urgent need for enhanced disaster planning and response taken into account the cascading effects of earthquake. It also highlights the importance of reinforcing urban planning, upgrading emergency infrastructure, and raising public awareness to mitigate future risks.

Keywords: GIS; KHM; multi-criteria analysis; geospatial techniques; sustainable development; vulnerability

1. Introduction

Earthquakes are among the deadliest natural hazards, frequently impacting major cities, causing substantial damage to buildings, and resulting in significant loss of life [1-2]. Reports from the United Nations highlight a rising frequency and intensity of earthquakes, leading to increasing damage. These trends clearly demonstrate the importance of assessing earthquake preparedness at the building level to minimise losses and fatalities. A comprehensive approach to earthquake preparedness must address all aspects of seismic hazards [3]. This includes evaluating the quality of construction, designing and implementing earthquake-resistant structures, and developing effective emergency response plans. Furthermore, it is essential to address the social, economic, and environmental impacts of earthquakes in line with Sustainable Development Goal 11 (SDG 11), which aims to create inclusive, safe, resilient, and sustainable cities and communities. The United Nations' SDGs, particularly SDG 11, focus on reducing the impact of natural hazards such as earthquakes on society and the environment. Urban areas are vital to global development, and their growth must be managed to ensure long-term sustainability for both current and future generations. SDG 11 encompasses ten key targets [4-5], including:

- SDG 11.1: Ensuring safe and affordable housing, including upgrading slums.
- SDG 11.5: Reducing disaster-related deaths and impacts, with a focus on protecting vulnerable groups.
- SDG 11.9: Implementing policies that promote inclusion, resource efficiency, and disaster risk reduction.

This study contributes to progress on SDG 11.1, 11.5, and 11.9 by addressing earthquake preparedness and urban resilience.

Assessing earthquake preparedness at the building level necessitates consideration of multiple factors, including the building's age, construction materials, design, and location [6]. This is particularly critical for older buildings, which are more susceptible to significant damage due to outdated construction practices. Moreover, earthquake preparedness should involve the development of emergency response plans at both the building and city levels to mitigate risks and minimise loss of life during disasters.

In urban emergency planning, adopting a comprehensive approach that incorporates multi-hazard analysis, including the consideration of cascading effects, is essential. The concept of multi-hazard analysis recognises that hazardous events can occur simultaneously, potentially leading to interconnected and cascading effects and compounded challenges [7-8]. By integrating preparedness measures for various hazards, cities can strengthen their resilience and response capabilities. Establishing clear and well-marked evacuation routes based on accessibility measures is vital, as these pathways guide residents and visitors to safety during emergencies. Providing safe and accessible shelters is equally important, as these facilities offer temporary accommodation for individuals displaced during disasters. Key considerations for shelters include their proximity to hazard-prone areas, capacity, and availability of basic necessities. Effective communication and transportation are the backbone of emergency response. Cities must develop robust networks that connect emergency services, first responders, and relevant agencies, ensuring rapid and coordinated action. Multi-hazard scenarios pose significant risks to urban areas, with impacts extending far beyond physical damage to buildings and infrastructure [9-11]. Such hazards can lead to fatalities, particularly in case of building collapses or when individuals are caught in hazardous situations. Survivors may sustain injuries caused by falling debris, structural failures, or panic during the event. Access to medical care and emergency services becomes critical in these circumstances. Furthermore, roads, bridges, utilities, and communication networks can suffer extensive damage, severely disrupting emergency response efforts. The repair and restoration of infrastructure are essential components of recovery. In summary, effective emergency planning must account for multi-hazard scenarios, prioritise robust communication systems, accessibility and strategies aimed at minimising social and economic consequences. By emphasising preparedness, cities can better protect their residents and enhance overall resilience [12-14].

A key element of effective emergency planning involves ensuring that communities are equipped with the necessary resources and information to respond promptly and cohesively to disasters. In this regard, building evacuation plans are one of the vital components of any comprehensive emergency response strategy. These plans provide critical guidance on safe evacuation routes, available shelter options, and communication channels for emergency responders. When well-structured and effectively implemented, evacuation plans can significantly reduce the risk of injuries and fatalities during disasters [15-16]. Streets and roads play an indispensable role during and after earthquakes by enabling search and rescue operations, access to essential facilities, and safe evacuation routes. However, earthquakes can result in significant blockages on streets and roads, creating severe challenges for emergency response efforts and escalates the overall impact of the disaster. These blockages may be caused by debris from collapsed buildings, landslides, and ground fissures [17-18]. The extent of such blockages and their impact on critical infrastructure – such as hospitals, water treatment facilities, and other essential services – can be substantial and long-lasting. Therefore, understanding the nature and implications of street and road blockages is crucial in devising effective and efficient earthquake preparedness and response plans [19-22]. The impact of earthquake on transportation networks and the resulting disruptions pose significant challenges for emergency responders. Strategic planning, resilient infrastructure development, and heightened community awareness are vital considerations for mitigating these effects and enhancing disaster response capabilities.

Natural hazards are inherently complex and cannot be effectively addressed through a one-dimensional approach. While specific hazard assessments may yield highly accurate results, they often fall short in providing comprehensive guidance for planners due to the unique conditions and triggering mechanisms of each region. Developing multi-hazard maps is a highly effective strategy for assessing vulnerabilities and mitigating the risks associated with natural hazards. In mountainous regions, earthquakes can trigger landslides, resulting in road blockages and extensive damage that complicate rescue operations. Landslides, as mass movement events, pose significant threats to human safety, the environment, and the economy [23-26]. Over recent decades, Geographic Information Systems (GIS) have been extensively utilised for studying natural hazards. Skilodimou et al. [27] used the hierarchical method within a GIS framework to produce a multi-hazard map, classifying areas according to vulnerability and identifying the most suitable locations for urban development. Similarly, Rehman et al. [28] employed the hierarchical method of frequency ratio within GIS to create a multi-hazard map for Muzaffarabad region, demonstrating its suitability for sustainable development and economic activities. Hashemi et al. [26] developed a GIS-based model to estimate earthquake-induced losses in a Tehran neighbourhood, focusing on building damage assessments, with a particular emphasis on ground effects. This research underscored the importance of GIS in understanding earthquake hazards and vulnerabilities within specific geographic contexts [6]. Additionally, Karimzadeh et al. [1] combined radar and optical imagery with deep learning methods to identify road damage caused by the Kumamoto earthquake. However, they did not thoroughly assess the preparedness levels of urban areas, particularly with regards to the impacts on accessibility for rescue operations and other related emergency responses.

Most studies have not adequately addressed the importance of multi-hazard assessments, often focusing on hazards in isolation. This approach overlooks the complex interplay of multiple factors, as many studies concentrates solely on the effects of earthquakes on mortality and structures, as well as impacts of floods and landslides in isolation [29-32]. However, in mountainous regions, a comprehensive assessment must consider multi-hazard scenarios, Currently, no studies provides an in-depth analysis of the combined impact of landslides and earthquakes, and their cascading effects on roads. This research aims to address this gap by investigating the combined and cascading effects of earthquakes and landslides on both buildings and roads. The main contributions of this study are threefold; (i) it integrates the Karmania Hazard Model (KHM) with the Analytical Hierarchy Process (AHP) to enhance risk assessment methodologies by analysing the interdependencies between earthquakes and landslides and their integration with other comprehensive data sets for city preparedness analysis; (ii) it provides comprehensive high resolution data on road blockages and proximity analyses of emergency routes, directly informing evacuation planning and identifying critical access points for effective emergency response; (iii) the research offers context-specific recommendations for disaster preparedness in Tabriz, advocating for policies that align with Sustainable Development Goal 11 (SDG 11) to improve urban resilience through inclusive and sustainable planning practices.

We conducted the scenario-based data generation in three main stages: data preparation, application of the Karmania Hazard Model (KHM) for a 7.3 Richter earthquake scenario, and the use of the AHP method to develop a landslide risk map. The AHP method has been already used for several risk mapping exercised in the literature including earthquake and landslide risk mapping [33-37]. We assessed structural damage, mortality rates, road blockages following the earthquake, and their intersections with landslide-prone areas. The goal was to address the lack of facilities and information in developing countries, particularly those prone to natural hazards. Iran, with its insufficient and incomplete environmental data, has experienced significant management challenges during disasters. This study provides a detailed examination of one of Iran's cities, highlighting its exposure and vulnerability to natural hazards. By simulating a 7.3 magnitude earthquake accompanied by landslides in the Tabriz mountains, the study underscores the critical need for comprehensive multi-hazard assessments, despite the limitations in data availabilities and scope. This study primarily focuses on road blockages caused by debris and landslides, employing a coordinated approach through GIS to tackle challenges related to street and road accessibility. By doing so, it aims to save lives, identify critical damage points, minimise overall harm, and streamline post-earthquake recovery efforts. Additionally, it evaluates the city's alignment with sustainable development goals, revealing significant gaps in achieving urban resilience and fostering sustainable development growth. Moreover, it calculates the distances of blocked routes for each structure and determines their proximity to the nearest accessible road. This aspect is particularly critical for countries with limited resources to conduct comprehensive regional assessments. By forecasting the extent of road blockages and availability of facilities, the study facilitates improved planning and preparedness. Overall, this study is particularly relevant for underdeveloped and mountainous cities, providing actionable insights for more effective planning and response to multi-hazard crises through scenario-based approaches.

2. Methodology

The methodology of this study provides a comprehensive framework for assessing earthquake-triggered multi-hazard preparedness analysis for Tabriz city through an integrated geographic information system (GIS) approach. It begins with a detailed analysis of the study area in Section 2.1, including geological conditions and population vulnerabilities, and is followed by the development of a geodatabase in Section 2.2 that incorporates essential data from various sources. The earthquake microzonation process, described in Section 2.3, employs the Analytical Hierarchy Process (AHP) to evaluate influential parameters and generate a site amplification map. This framework is further enhanced by considering the vulnerabilities of buildings in Section 2.4, landslide risks in Section 2.5, road accessibility in Section 2.6, and population dynamics in response to potential seismic events in Section 2.7. The methods employed not only aim to improve existing hazard models but also to simulate a realistic earthquake scenario, thereby offering valuable insights into the complex and multifaceted nature of earthquake risk in Tabriz.

2.1. Study area

The study focuses on Tabriz city, shown in Figure 1, a major city in Iran with a population of over 1.8 million. This area is particularly vulnerable due to its proximity to the Tabriz fault in the northern region, where a highly at-risk population resides and is exposure to multiple natural hazards.

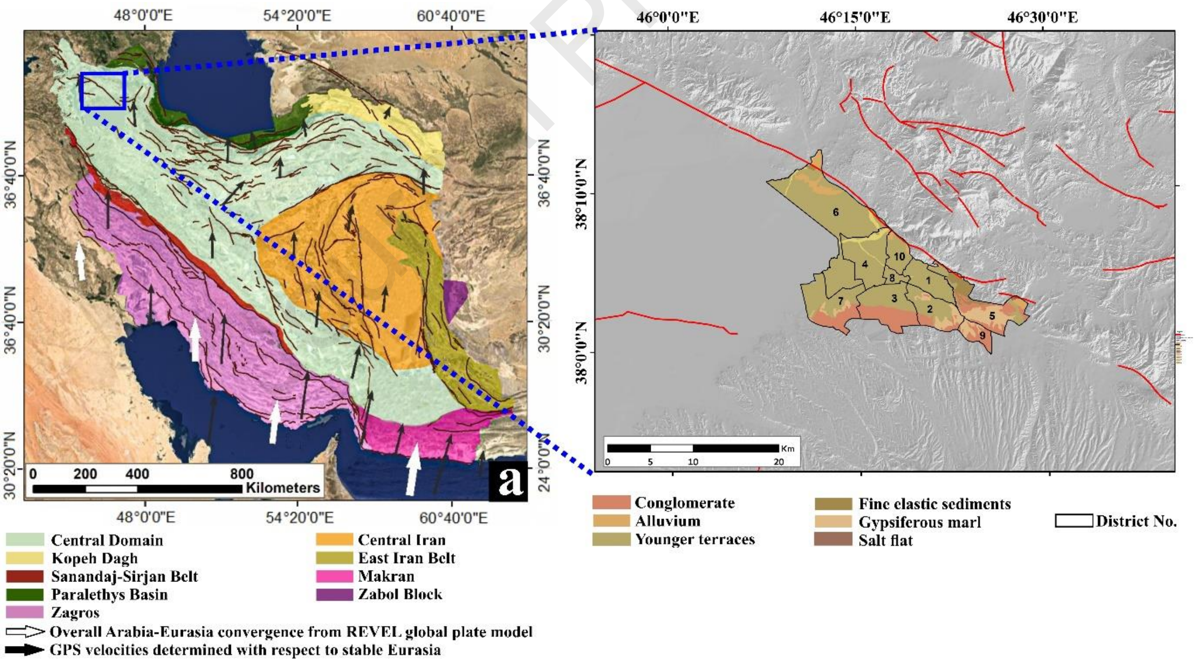

Figure 1. (a) The sedimentary and structural seismic conditions in Iran based on Aghanabati's classification (2004) [38]. (b) Spatial location of the major fault within the study area and the geological conditions of the district.

In this study, we used an integrated GIS approach based on spatial analysis methods to conduct a comprehensive and multidimensional analysis of the 7.3 Richter earthquake scenario [39]. Our research highlights the absence of a unified model for earthquake risk. Several methods were designed, including the Karmania Hazard Model (KHM) for Iran, designed to assess building and human damages [40]. The aim of this study is to enhance this model to improve its accuracy and realism. To achieve this, we incorporated the influence of landslide risk in blocking roads, which increases the fatality rate. We prioritised the KHM as an interactive environment, combining spatial layers of building vulnerability coefficients and population data, making it suitable for earthquake scenario modelling. This model is flexible, allowing modification of spatial layers based on district-specific vulnerability coefficients, enabling the integration of road vulnerability and landslide hazards. The model has been tested and evaluated against the Bam earthquake, Sarpol-e Zahab earthquake, and the results are applicable to various environments, including both mountainous and desert regions. The general principles of our work are shown in Figure 2, which outlines three main steps, as detailed below.

As shown in Figure 2, this study consists of three main processes: the preparation and aggregation of information from various sources, the assessment of environmental conditions using decision-making method to evaluate earthquake risks, and the damage assessment process, all of which are described further below.

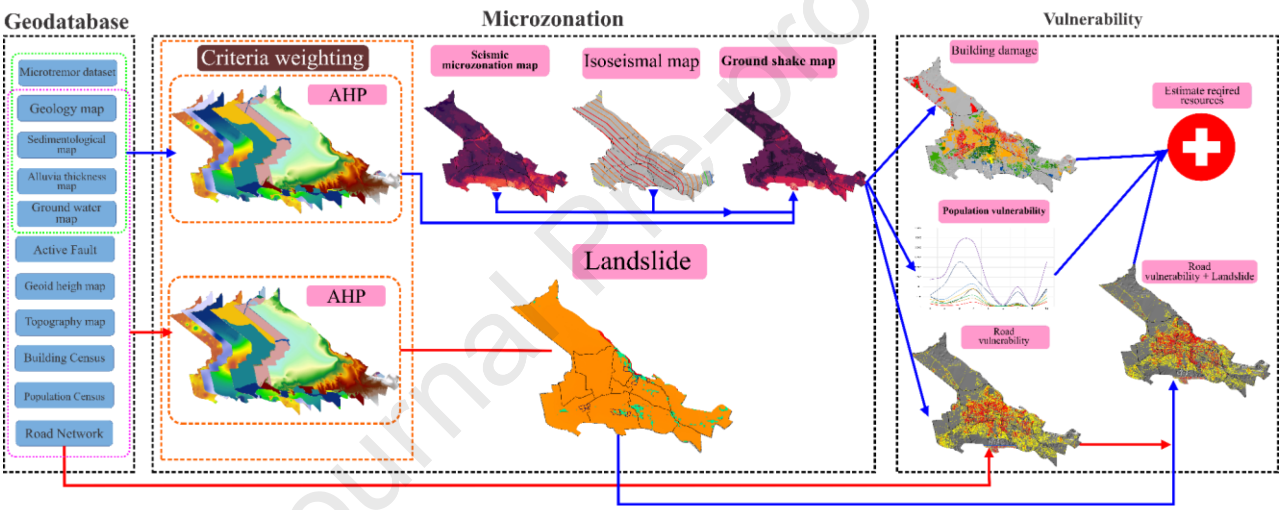

Figure 2. The general technical process of investigating multiple risks for the city of Tabriz consists of three keys stages: obtaining information from various organizations, conducting microzonation, and assessing the vulnerability of buildings, streets/roads, and the population.

2.2. Geodatabase

The required data are listed in Table 1, along with the necessary information for conducting the optimised model. Field evaluations were carried out to develop and assess the Tabriz earthquake scenario, which occurred historically in 1721 with a magnitude of 7.3 on the Richter scale [41]. The GIS data layer of streets, buildings and temporary settlements were obtained, verified and corrected through ground-based surveys and official reviews. Additional information was sourced from relevant organisations, including the Crisis Management Organisation, Municipality, Surveying and Mapping Organisation, and the Planning and Budget Organisation. All layers were converted to shapefiles and integrated into a geodatabase. It should be considered that Tabriz is a large metropolitan area with high-pressure electricity, gas, water and sewerage networks running beneath many of its buildings. Due to the unavailability of this data, these networks were excluded from the analysis, and it is assumed that, in case of natural hazards, they would be temporarily cut off.

Table 1. KHM Model Database for 7.3 Richter Earthquake.

Database	Type	Source
Earthquake catalogue	vector	www.iiees.ac.ir
Active fault	vector	www.ncc.gov.ir
Ground water	raster	www.ncc.gov.ir
Geology map	raster	www.ncc.gov.ir
Sedimentological map	raster	Karimzadeh et al., 2014 (36)
Alluvia thickness map	raster	Karimzadeh et al., 2014 (36)
Microtremor dataset	raster	Karimzadeh et al., 2014 (36)
Building census	vector	www.tabriz.ir
Slope	raster	www.ncc.gov.ir
Landuse	vector	www.tabriz.ir
Topographic map	raster	www.ncc.gov.ir
Road dataset	vector	www.traffic.tabriz.ir
Landslide	vector	www.ncc.gov.ir
Population census	vector	www.tabriz.ir

2.3. Earthquake Microzonation

The earthquake microzonation in this study was conducted using influential data and the Analytical Hierarchy Process (AHP) decision-making model [40] (Figure 3).

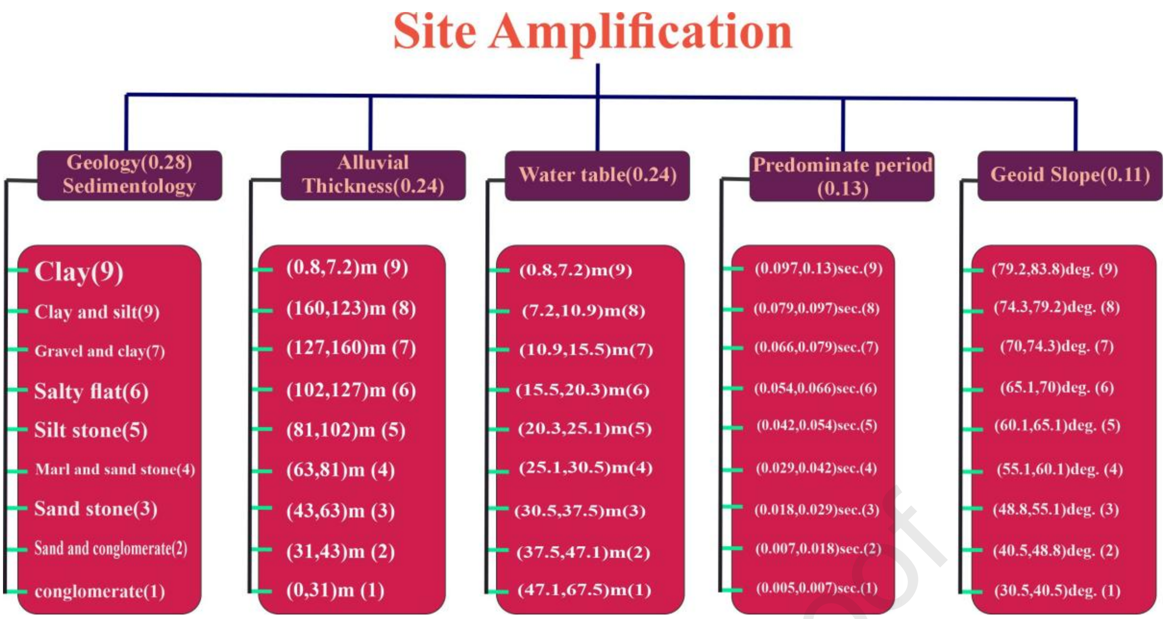

Figure 3. represents the weighting of parameters influencing earthquakes based on the Analytical Hierarchy Process (AHP) decision-making method.

The first step involved preparing the influential parameters for seismic microzonation of the Tabriz metropolitan area in the form of a comprehensive and reliable database. In this part of the study, a thorough review of various research in this field, especially considering the specific conditions of the region, led to the selection of relevant parameter by experts. Some parameters were omitted due to limited access to or absence of reference data. Only accessible and validated parameters were used in the analysis. The selected parameters are presented in Table 1. The identification of site effects on earthquakes is one of the most important factors in this model, determined using various criteria [17,26,28,41,42]. The most significant factors in microzonation include geotechnical characteristics [17], such as geological layers, sediment thickness, microtremors, slope, and groundwater levels. These factors were utilised, and the seismic microzonation map of Tabriz was obtained through the AHP weighting method. AHP is highly suitable for multi-criteria decision-making and environmental data evaluations. To generate the site amplification map, the weights obtained from the hierarchical weighting method were applied to the relevant layers, which were then summed together and normalised to produce the final map [41]. According to expert opinion, geology was considered more important than other factors. The final site amplification microzonation map was obtained using the following equation:

$$AI = \sum(G_i \times M_i \times T_i \times W_i \times S_i) \quad \text{(Eq.1)}$$

In Equation 1, AI represents the site amplification map in a specific district, which is the sum of geological and lithological layers (G_i), seismic period of the site (M_i), sediment thickness (T_i), groundwater conditions (W_i), and topographic slope (S_i).

Determining seismic sources is one of the most important steps in earthquake scenario development. The fault map is prepared based on satellite images and geological maps, with active faults and seismic sources identified using aerial photos and field studies. For defining earthquake scenarios, the length, azimuth angle, and magnitude of each earthquake are measured based on fault parameters. The worst-case scenario for the most unstable fault segment is identified using Equations 2 [43] and 3 [44].

$$Ms = \log L + 5.4 \qquad \text{(Eq. 2)}$$

$$Ms = ((\log L + 0.126) / 0.675) \qquad \text{(Eq. 3)}$$

Ms represents the surface wave magnitude, and L is the fault length, typically considering 50% of the fault length.

Earthquake hazard at a site is typically defined based on the ground motions generated by earthquakes at that location. Its characteristics are usually determined by one or more ground motion parameters derived from empirical and theoretical relationships.

Table 2. Fault Parameters of the Earthquake Source.

NW(NTF)	**Descriptions**
Starting point in UTM coordinates (X, Y)	(624555.925,4213508.213)
Ending point in UTM coordinates (X, Y)	(584957.047, 423450.388)
Reference point in UTM coordinates (X, Y)	(606924.994, 422636.423)
Magnitude (Mw)	7.3
Length (km)	45
Strike (deg.)	270
Dip (deg.)	90

Subsequently, using the data from Table 2, we simulate the main fault of Tabriz with the characteristics matching those of the 1721 earthquake. Additionally, the distance relationship of each cell is described by a source, and this distance is used as the corresponding attenuation coefficient. The distance is measured from the fault up to 150 kilometres. In this study, we employ Modified Mercalli Intensity (MMI), which is derived using region-specific formulas to determine the earthquake intensity. Intensity attenuation in relation to distance from the epicentre has been studied extensively, and specific coefficients have been applied for different areas. Research on attenuation in Iran has been conducted, with the most significant studies, used in this research, presented below. The following equations, derived from Ambraseys, Melville, and Chandra, were calculated for the study area range [45]:

$I_0 = 1.3M_s + 0.09$ (Eq. 4)

$I = I_0 + 0.453 - 0.00121R - 4.96\log(R + 20)$ (Eq. 5)

In Equation 4, 5, I represent the intensity at a distance of R kilometres from the surface fault, and M_s represents the earthquake magnitude on the surface wave scale.

The attenuation relationships indicate the level of earthquake intensity that each point within the affected area can withstand. Since these relationships are based on PGA (Peak Ground Acceleration) and PGV (Peak Ground Velocity), and considering that the vulnerability curve of Iran's structures was derived from Modified Mercalli Intensity (MMI), the PGA, PGV method was not used. The attenuation relationships were derived using Equation 1 to obtain MMI (Figure 4).

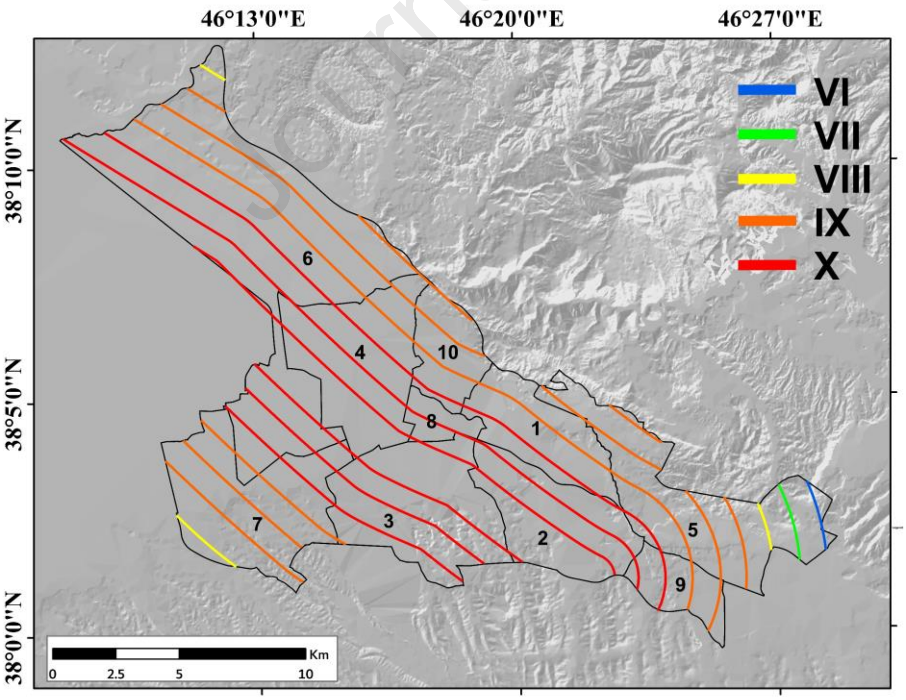

Figure 4. Intensity map of a 7.3 magnitude earthquake (the Roman numerals represent the Modified Mercalli Intensity).

To generate the final ground shaking map based on the MMI scale, Equation 6 is applied, integrating the raw earthquake intensity map from Figure 1 with the detailed site classification map (Figure 4).

GSM = $\sum M_i \times I_i$ (Eq. 6)

2.4. Buildings vulnerability assessment

Buildings are constructed differently across countries, resulting in varying responses to earthquakes. Numerous studies have been conducted to assess the vulnerability of buildings, taking into account their distinct construction methods. For instance, the 2008 JICA study developed vulnerability curves for Iranian buildings, drawing on data from previous earthquakes. These curves are developed based on the Modified Mercalli Intensity (MMI) scale and classify buildings according to their construction type and number of floors [46].

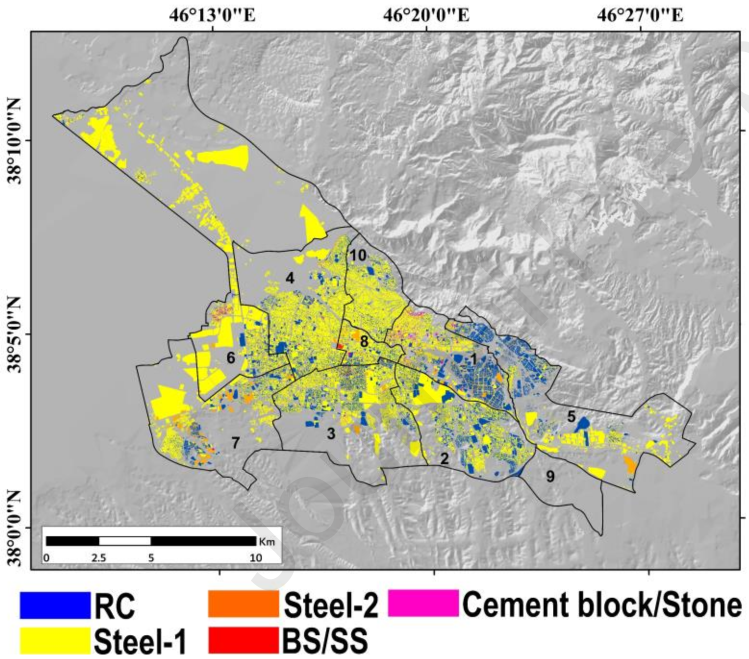

Figure 5. The distribution of buildings within the studied area in terms of their structural types, with predominant type being Steel-1, which consists of metal structures of up to three storeys.

The building map was prepared by the Housing and Urban Planning Organization. Given the slow pace of data updates in a country like Iran, the received data was thoroughly reviewed and revised to align with the latest changes. Table 3 and Figure 5 show the status of structures in Tabriz city. RC (Reinforced Concrete) buildings vary in number of storeys. The highest density is observed in districts 2 and 5, while the lowest in district 10, which accounts for only 6.4% of the total. Approximately 19.5% of the city's structures are reinforced concrete buildings. Steel-1 buildings, which are metal structures with up to three storeys, and are most common in district

4, where they represent 84% of the structures. Steel-1 buildings dominate Tabriz, comprising 70.8% of the total. Steel-2 buildings are metal structures with more than three storeys, with the highest proportion found in district 2, making up 35% of Steel-2 buildings and 7.5% of the total in Tabriz. BS/SS refers to structures with masonry walls, typically older buildings located in suburban areas. District 1 has the highest proportion of BS/SS structures, accounting for 9.4%, mostly located in the outskirts of Tabriz. These buildings are highly vulnerable to earthquakes and pose significant risks to access routes. Cement block structures, which are constructed entirely from cement blocks, are relatively rare. Figure 5 illustrates the spatial distribution of various structural types, showing that the northern districts of Tabriz and a much of district 4 have dilapidated and vulnerable buildings. District 5, managed by Tabriz Municipality, is in a better condition, with newer buildings and a more affluent, educated population. However, district 10 and the western part of district 1 feature inadequate structures, inhabited by vulnerable populations, including migrants from surrounding villages. These areas have been marginalised, lacking basic facilities, city services, and accessibility.

As shown in Figure 5, the southern part of Tabriz demonstrates a highly favourable condition, exhibiting significant resistance to earthquakes. District 2 and 3 also show relatively favourable conditions., with the eastern part of district 5 being in better shape than its western counterpart. On the other hand, the central and northern parts of Tabriz, especially district 1-10, are in very unfavourable conditions and have low resistance. These areas are characterised by their proximity to the fault line, thin soil layers, loose soil, and poor geological conditions. District 9, a newly established areas designed in line with the city's engineering and developmental goals, is sparsely populated but has favourable conditions and aligns with the objectives of the Sustainable Development Goals (SDGs).

Table 3. Percentage distribution of types of urban structures based on each urban area

	RC%	Steel-1%	Steel-2%	BS/SS%	Cement block%
District 1	21.4	62.0	7.2	9.4	0
District 2	33.4	31.6	35.0	0	0
District 3	26.0	68.6	5.1	0.3	0
District 4	12.3	84.7	2.4	0.6	0
District 5	54.1	38.58	7.2	0.1	0.02
District 6	13.4	76.0	5.4	4.6	0.6
District 7	17.0	78.0	5.0	0	0

District 8	15.2	78.7	5.5	0.6	0
District 10	6.4	85.2	5.1	3.3	0
Total %	19.5	70.97	7.5	2	0.03

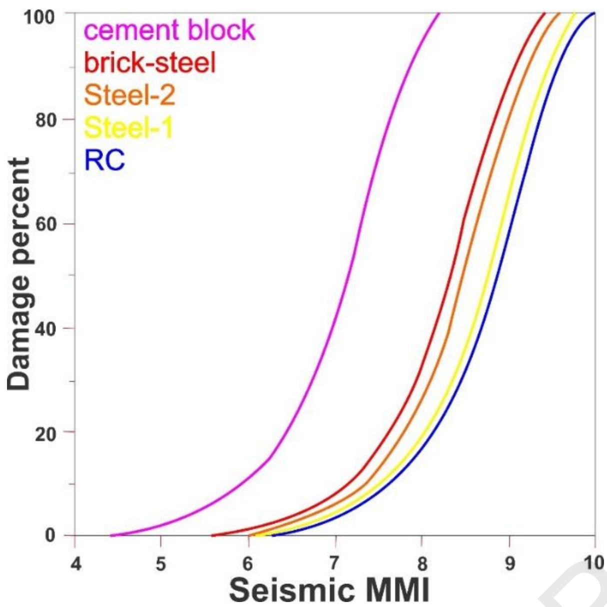

Figure 6. Vulnerability Curve of Buildings based on Modified Mercalli Intensity (33, 39)

Figure 6 illustrates the percentage of damage based on Modified Mercalli Intensity (MMI) for different types of structures. According to the vulnerability curve, weaker structures such as cement block and wooden buildings are highly susceptible to even mild earthquakes, resulting in significant damage. At an intensity level of 7, these types of structures typically sustain severe damage, often resulting in very high levels of destruction (D2). In contrast, the damage rate in other types of structures is less than 20%. Based on observations from documented earthquakes, the destruction levels were categorized into six classes. The highest level of destruction, D1, exceeds 80%, while the lowest level, D6, is presented in Table 4.

Table 4. Classification of the level of building destruction based on Hassanzadeh et al.'s study (37,45).

Destruction level	**Percent of damage**	**Description**
No destruction (D6)	0-2	The structure is essentially intact, with no damage or only very minor damage
Light destruction (D5)	3-10	Very tiny cracks

Moderate destruction (D4)	11-30	5-20mm cracks are observed in the building
High destruction (D3)	31-60	> 20mm cracks are observed and some component of building such as wall are destroyed
Very high destruction (D2)	61-80	A part of roof and one building's wall is destroyed
Completely destroyed (D1)	81-100	Entire of roof and more than one building's wall destroyed

2.5. Landslide

Landslides are one of the hazards associated with earthquakes, especially in mountainous areas. Following an earthquake, landslides are likely to occur in such areas. Given that Tabriz is located on a fault line and the soil in northern Tabriz is loose and unstable, it is highly prone to landslides triggered by earthquakes. The occurrence of an earthquake can further activate movement along the Tabriz fault [24]. The consequences of such an earthquake can lead to rapid changes in the district, causing significant environmental and infrastructure damage, with the destruction of the northern Tabriz highway being one of the most significant impacts. The largest landslide in Tabriz is associated with the 1956 earthquake, with a magnitude of 7.2 on the Richter scale, which caused substantial landslides [48].

Since this study focuses on multi-hazards, we identified seven factors, based on expert opinions and various studies, as key determinants to evaluate the city's resilience to landslides and to assess the vulnerability of the city due to landslides. These factors were selected according to the study area's specific conditions and available information. Landslide occurrence is determined in the GIS environment. These factors include slope degree, elevation above mean sea level, distance from the fault, distance from rivers, distance from natural gas networks, soil type, and lithology [27,34-36]. It is worth mentioning that the study area is considered on a local scale and exhibits homogeneous conditions in terms of climatic variables. As a result, the precipitation criterion was excluded (Figure 7). The AHP method was then employed to generate a landslide susceptibility map [49]. The classifications of 'low,' 'moderate,' and 'high' susceptibility on the final landslide map were established using the natural break (Jenks) method. This statistical approach identifies optimal breakpoints within the susceptibility data, grouping similar values while maximizing the difference between classes. Consequently, areas are categorised based on their relative susceptibility levels, with each class representing a distinct range of susceptibility scores derived from AHP analysis. This method allowed us to delineate susceptibility levels meaningfully and based on inherent data distributions.

We have adopted a classification-based approach to estimate the impact on road accessibility across varying sensitivity levels. Specifically, areas classified as high-sensitivity zones are assumed to experience complete road blockages, rendering all routes impassable. For medium-sensitivity areas, an estimated 50% of road segments are considered blocked, reflecting moderate but significant disruption. Conversely, roads within low-sensitivity zones are anticipated to remain fully accessible, as these areas are less prone to landslide impacts. This classification method provides a structured, assumption-based framework to assess road blockage severity due to landslides, leveraging sensitivity zoning to systematically estimate and convey the degree of exacerbation. These levels allow for a clear interpretation of landslide effects on road infrastructure, supporting a quantifiable measure of landslide-induced road damage that can be further validated with additional data in future studies.

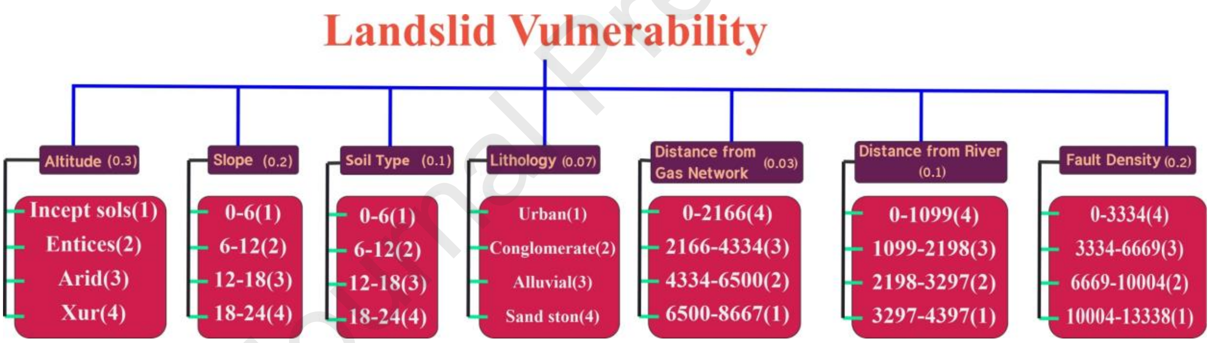

Figure 7: Weighting of parameters influencing landslide susceptibility using the Analytic Hierarchy Process (AHP) decision-making method.

2.6. Road blockage

Roads are considered as a key factor in emergency response and play a crucial role in traffic control and rescue operations. The presence of any structure alongside the road can cause road blockages. Open spaces and wide streets have a lower vulnerability to earthquakes, as mentioned in the structural section. North Tabriz faces a particularly challenging situation with a concentration of informal settlement and substandard shelters with minimal facilities. Due to the high building density in many areas, roads are not suitable for vehicle access, as observed during field studies. After an earthquake, roads could become blocked by building rubble and debris, which is especially critical in marginal areas where the narrowest streets are located (districts 1-10) and in district

4, due to its aged urban fabric that lacks proper infrastructure. Tabriz's historical district (district 8) also features narrow streets that complicate access. This study uses the following method to assess the level of road blockage:

Volume of building = $Area\ of\ ground\ floor \times Number\ of\ stories \times Height\ of\ each\ floor$ (Eq. 6)

In Tabriz, two types of construction exist: illegally constructed spaces in marginal areas with no yards, accounting for 100% of the constructed land; and structures built according to engineering standards, where 60% is built-up area and 40% is yard. This study considers the latter case. Equation 6 calculates the volume of the building, and Equation 7 calculates the volume of construction materials for each building developed by local civil engineers [26]. The demolition coefficient is then applied, and Equation 8 calculates the volume of debris.

Volume of construction materials = $Volume\ of\ building\ /\ 5$ (Eq. 7)

Volume of waste materials = $Volume\ of\ construction\ materials \times Percent\ of\ building\ damage$ (Eq. 8)

Area of waste materials = $(Volume\ of\ waste\ materials)\ /\ (Height\ of\ waste\ materials)$ (Eq. 9)

To calculate the area occupied by debris, an assumed height of 1 meter is considered, and Equation 9 is applied. Finally, the area of streets occupied by debris from each adjacent building is calculated using Equation 10. It is also important to consider the distance between the building and the street [50]. The direction of collapse is taken into account as well. For example, if a building is blocked on three sides but open at the front, the debris will fall towards the front only. However, if the building is open on three sides, the debris will be distributed across all three sides.

Occupied area of adjacent street = $Occupied\ area\ of\ the\ adjacent\ street - Area\ of\ ground\ floor$ (Eq. 10)

In the secondary section, earthquake-induced landslides impact loose soils, and the results of landslide susceptibility indicate the city’s vulnerability to landslides. Therefore, the potential impact of landslides on infrastructure is considered. In fully developed areas where there is no bare soil, it is assumed that landslides will not significantly affect roads. In addition to these considerations, traffic movement was entirely eliminated from the analysis, with roads declared one-way due to the crisis conditions.

2.7. Population Vulnerability

In contemporary societies, the primary goal of emergency response is to save human lives, and in sustainable development, providing adequate shelter is considered essential. In the city of Tabriz, the population exceeds 1,800,000 people. Figure 8a illustrates urban density, with 25% of the population living in marginal areas that are highly vulnerable [51]. From an economic and social perspective, housing, healthcare, urban facilities, and services are at the lowest levels of welfare, lacking access to sustainable housing, with the wealthiest class residing within a short distance of these areas. This affluent class enjoys the highest economic and social status, benefiting from better housing, healthcare, urban facilities, and services, along with ample green and recreational spaces. In terms of both structural and population density, the marginal and older areas of Tabriz, particularly district 4, exhibit high density. However, district 8 has the lowest population density but serves as Tabriz's economic hub, attracting a large influx of people from various areas during the day. The highest urban density is observed in district 10, followed by the western part of district 1 and the northern part of district 4. In terms of population, district 4 has the highest number of residents.

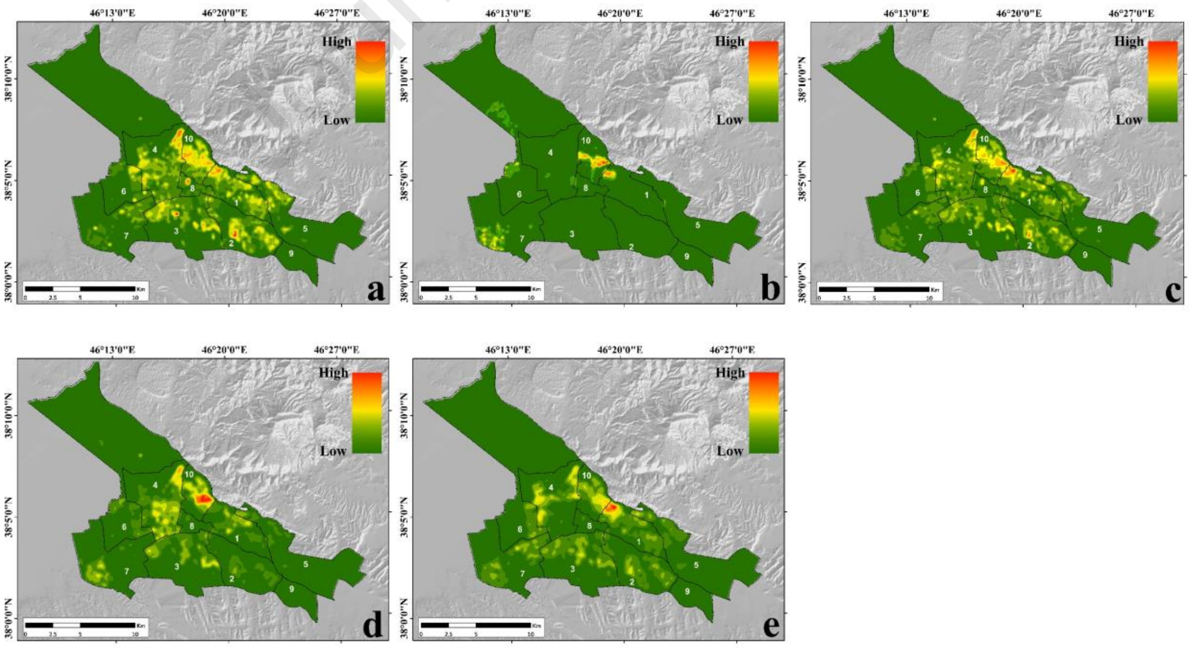

Figure 8. a) represents the population density in different areas of Tabriz municipality. b) The population density of illiterate individuals in different urban areas. c) The population density of literate individuals in different urban areas. d) The

population density of children under ten years old in different areas of Tabriz city. e) The population density of individuals above ten years old in different areas.

Population datasets are typically obtained through censuses. In this study, the statistical data from the 2020 yearbook of Tabriz Municipality was employed. According to Figure 8a, districts 1, 4, and 10 exhibit the highest population densities among the various areas of Tabriz Municipality. Consequently, these areas also show high building density, while per capita road availability is significantly lower. The average area of buildings in these three districts is less than 70 square meters. Conversely, district 8, while the least populated, experiences significant fluctuations in population density throughout the day, making it the busiest area with predominantly commercial activity.

In Figure 8b, the population density of illiterate individuals is higher in districts 1 and 10. These individuals typically work in lower-paying jobs and have migrated from surrounding villages to these districts. Figure 8c illustrates the population density of literate individuals with education up to a high school diploma, which is distributed across all urban areas, including suburban regions. The youth in these areas seek social mobility and strive to improve their social status, influenced by the populations in other areas. Figure 8d depicts the population density of children, with the highest concentration found in district 10. However, this area has the lowest educational resources and green spaces, and is prone to high-risk urban settlements, making children the most vulnerable age group in terms of earthquake impacts.

As shown in Figure 8e, the population over ten years old is distributed relatively evenly across all areas, with the highest density observed in districts 4 and 10. The report utilises the findings of vulnerability functions presented by JICA [46] and refers to the solutions proposed by Coburn et al. [52]. Based on JICA studies [48], the relationship between fatalities caused by past earthquakes in Iran indicates that casualties remain low up to an intensity of eight, at around 10%, but suddenly increase to 50-80% at intensities nine and ten. Another significant difference in casualties is noted between night and day. Fatalities during nighttime, when residents are indoors, are significantly higher compared to daytime, when people are outdoors or in more resilient structures, such as workplaces.

As shown in Table 5, building destruction is categorised into six levels. Based on this classification, the occupants of each category have coefficients that determine the loss rate, as presented in Table 5. At the D1 intensity level, the most destruction of buildings is observed, with 41% of occupants killed, while 22% remain unharmed [52].

Table 5. Expected degree of casualties in each specific vulnerable district based on previous earthquakes (KDMC, 2008)[40].

Type of destruction	**Status of people**	**Casualty rate**	**Type of destruction**	**Status of people**	**Casualty rate**
No Destruction	Dead	0	High destruction	Dead	13
	Hospitalized	0		Hospitalized	17
	not hospitalized	1		not hospitalized	23
	Not injured	99		Not injured	47
Light destruction	Dead	2	Very high destruction	Dead	16
	Hospitalized	5		Hospitalized	22
	not hospitalized	9		not hospitalized	28
	Not injured	84		Not injured	34
Moderate destruction	Dead	4	Completely destroyed	Dead	41
	Hospitalized	9		Hospitalized	16
	not hospitalized	15		not hospitalized	21
	Not injured	72		Not injured	22

3. Results

3.1. Earthquake Microzonation

In this study, we updated the parameters by consulting experts, and then used the AHP weighting method to prepare the site amplification. This amplification was subsequently combined with the earthquake intensity map to create the ground shaking intensity map, which was used to assess the vulnerability of buildings and roads (Figure 9).

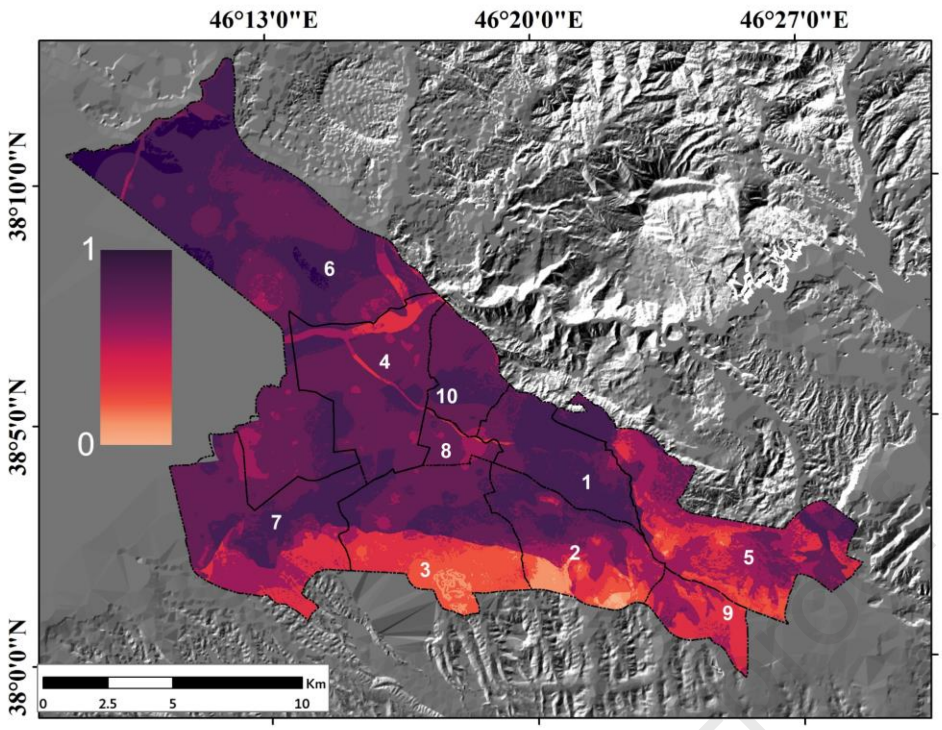

Figure 9. Final analytical hierarchy process adoption for the influential parameters.

Through an examination of the existing construction conditions, this study revealed that many areas within the study zone are unsuitable for development and require planning and evacuation. The expansion of Tabriz city has occurred predominantly in the northern direction, which contravenes safety principles. In contrast, the southern part of city presents a better environment for development.

The seismic intensity map (Figure 10) illustrates the effects of a 7.3 magnitude earthquake at its historical epicentre, aligned with the main Tabriz fault. This map highlights the impact of the raw earthquake intensity on site conditions. The marginal districts 1-10 and the western part of district 1 are projected to experience the highest level of damage, with a modified Mercalli intensity of 9. In these areas, intensity levels will peak, whereas the southern districts, as shown in Figure 10, will exhibit the lowest intensity levels, at a modified Mercalli intensity of 6. In certain areas with weak site conditions and proximity to the epicentre, damage is anticipated to be significant, with intensity levels ranging from 7 to 9. District 5 displays unique site response characteristics, while district 4, being the most densely populated urban area, will be affected by a modified Mercalli intensity of 7-9.

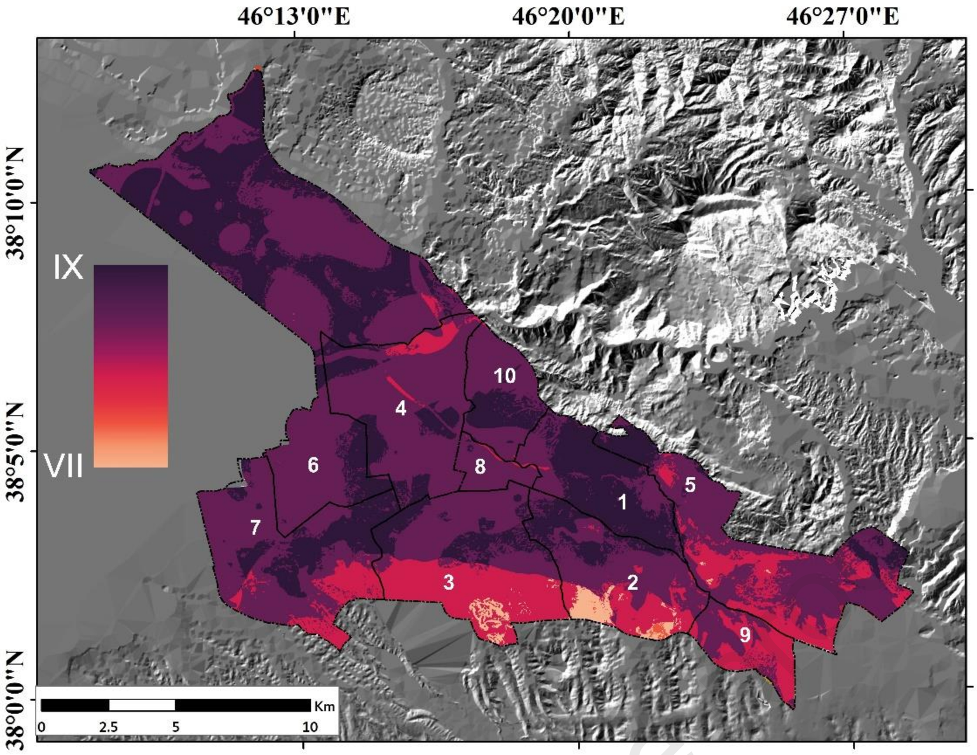

Figure 10. The final map of ground shaking intensity for a 7.3 Richter earthquake based on the Modified Mercalli Intensity (MMI) scale.

3.2. Landslide

Before embarking on any rescue or relief efforts, acquiring accurate environmental information is essential. In mountainous districts, landslides occur naturally but are exacerbated by human activities. While sustainable development aims to create stable environments, Tabriz city has unfortunately taken several inappropriate actions in this regard. Clearing vegetation and constructing structures on steep slopes and faults have resulted in significant damage to city’s environmental resilience.

This study aimed to investigate multi-hazard scenarios, particularly earthquakes, landslides and their cascading effects, to assess the impacts of earthquakes on structures and various locations within the study area. The findings indicate the city’s vulnerability to landslides, especially in the northern districts, including the marginal areas where unstable residential buildings have been constructed. Landslides triggered by earthquakes are among the major geological hazards in mountainous and hilly districts and represent one of the primary effects of earthquakes. Under specific conditions, post-seismic effects can be as significant as the seismic effects themselves. These conditions relate to natural slopes in active tectonic districts, where seismic shaking can weaken rock masses or soils, facilitating their descent down hillslopes and increasing erosion. Landslides involving damaged rock masses or loose soils are particularly prominent.

According to the results, the northern parts of districts 1 and 10 exhibit high vulnerability. District 2 also experiences high vulnerability due to the presence of steep slopes in certain areas. The central part of Tabriz city has moderate vulnerability. Figure 11 illustrates the locations of vulnerable areas, where a significant population resides near landslides and is at risk. In the event of an earthquake, these areas will face extensive damage alongside steep slopes. Additionally, developed areas in districts 1 and 5 are also exposed to landslides, as depicted in the accompanying images. As shown in Figure 11, the northern part of Tabriz has unfavourable conditions; however, the main northern highway traverses this area and has been obstructed multiple times due to landslides triggered by surrounding earthquakes. In contrast, the southern highway of Tabriz city does not pose any threats.

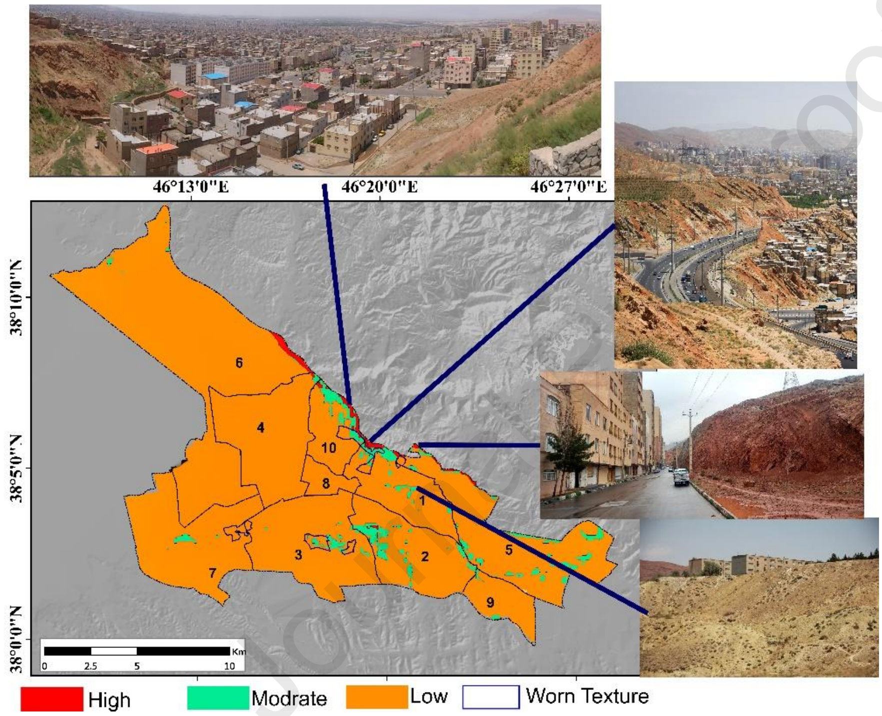

Figure 11. Vulnerability status of Tabriz city in terms of landslide susceptibility.

3.3. Building damage

The most significant impact of an earthquake on a city is its effect on the city's infrastructures and buildings. Regardless of the structural conditions, preserving lives and maintaining economic and social stability is paramount. Tabriz is a growing metropolis, but sustainable development in the city is progressing slowly, particularly in its northern districts. The western areas of District 1, District 5, District 2, and the northern part of District 3 are expanding, with new structures being constructed using reinforced concrete.

Structures are significantly affected by earthquakes, and the extent of damage varies depending on the Modified Mercalli Intensity (MMI) and the type of structure. In 2008, JICA developed fragility curves for Iranian structures, illustrating the damage each structure may sustain based on the MMI [41, 46]. The northern part of District 3 is not experienced favourable conditions regarding foundation stability and the intensity of shaking. However, with building upgrades, conditions in these areas could improve.

Approximately 52% of the structures in Tabriz are expected to suffer destruction ranging from 60% to 100%, with District 4 being the most severely affected, accounting for 75% of this damage and comprising 60,135 buildings. District 1 follows with an expected 50% destruction rate. Moreover, 21% of all structures in the city will experience destruction between 80% and 100%, with District 10 having the highest proportion, representing 46% of the total destruction, while District 1 accounts for 43%.

Samples from the structural conditions in Districts 1 and 10 reveal the accessibility and structural integrity of these areas (Figure 12). The lowest levels of damage are anticipated in Districts 2, 3, and 7, attributed to their distance from potential earthquake epicentres, better foundation conditions, and improvements in building standards. District 8, a historical and commercial hub of Tabriz, hosts a large daily population. The results indicate that this district will experience significant destruction, particularly in the covered bazaar, which is characterised by extensively damaged structures and the highest destruction coefficient. Providing assistance within this bazaar poses considerable challenges.

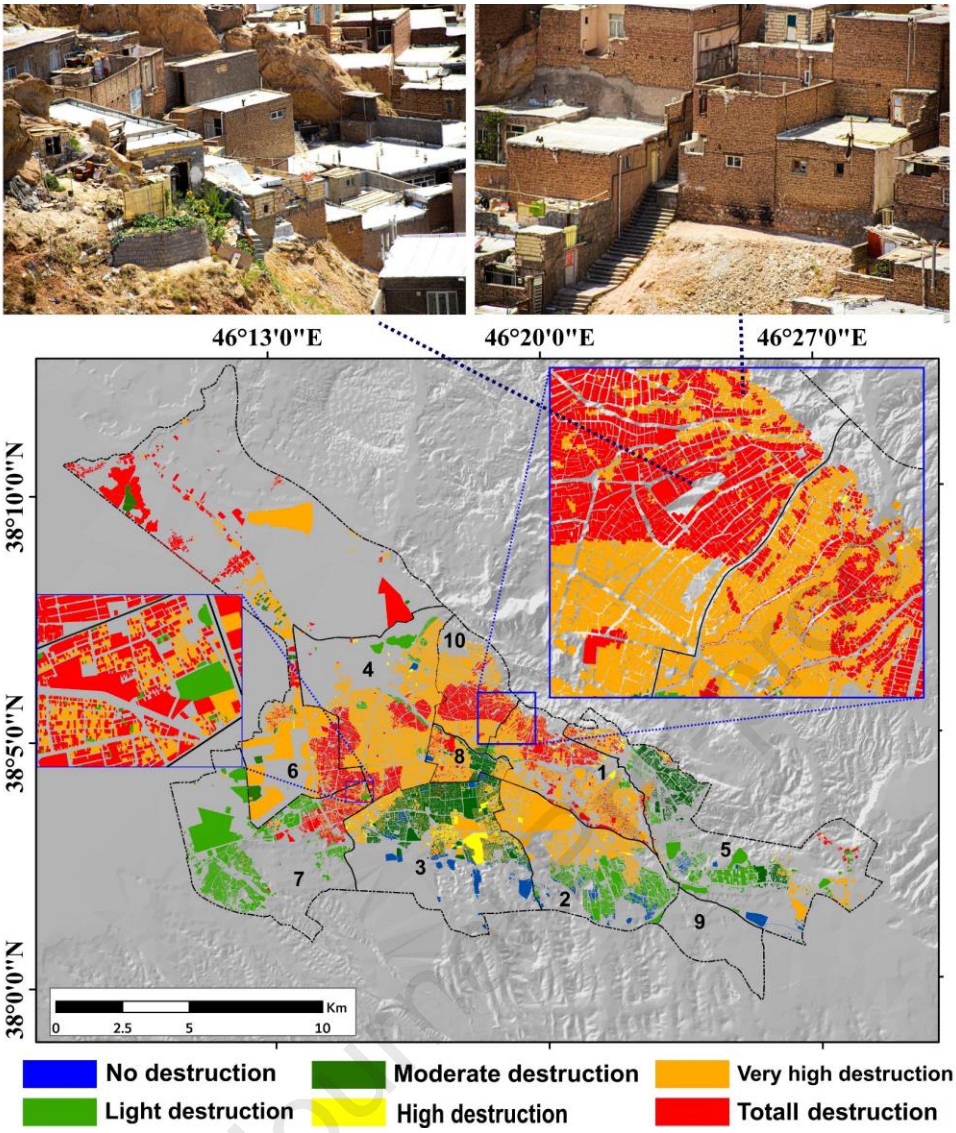

Figure 12. Location of structural damage in the city of Tabriz during the 7.3 Richter earthquake.

3.4. Road blockage due to building demolition and landslides.

Demolished buildings significantly impact road blockage and accessibility in Tabriz. There is a direct correlation between the level of destruction and the extent of road blockage throughout the city. In areas with high levels of destruction, road blockages have markedly increased. Overall, approximately 40% of the streets in Tabriz are completely obstructed, with District 4 experiencing the highest level of blockage at 60%. District 10 is similarly affected, with a blockage rate of 54%, while District 1 was also seen widespread obstructions.

In the eastern part of District 1, planned development and wide main streets were compromised by severe damage from buildings constructed outside of regulations. The volume of these structures has exceeded the street capacity, resulting in blockages across most thoroughfares. This district is completely surrounded by high-rise buildings, and over 55% of the secondary and local roads connecting to Districts 1, 4, 8, and 10 are obstructed (see Figure 13a).

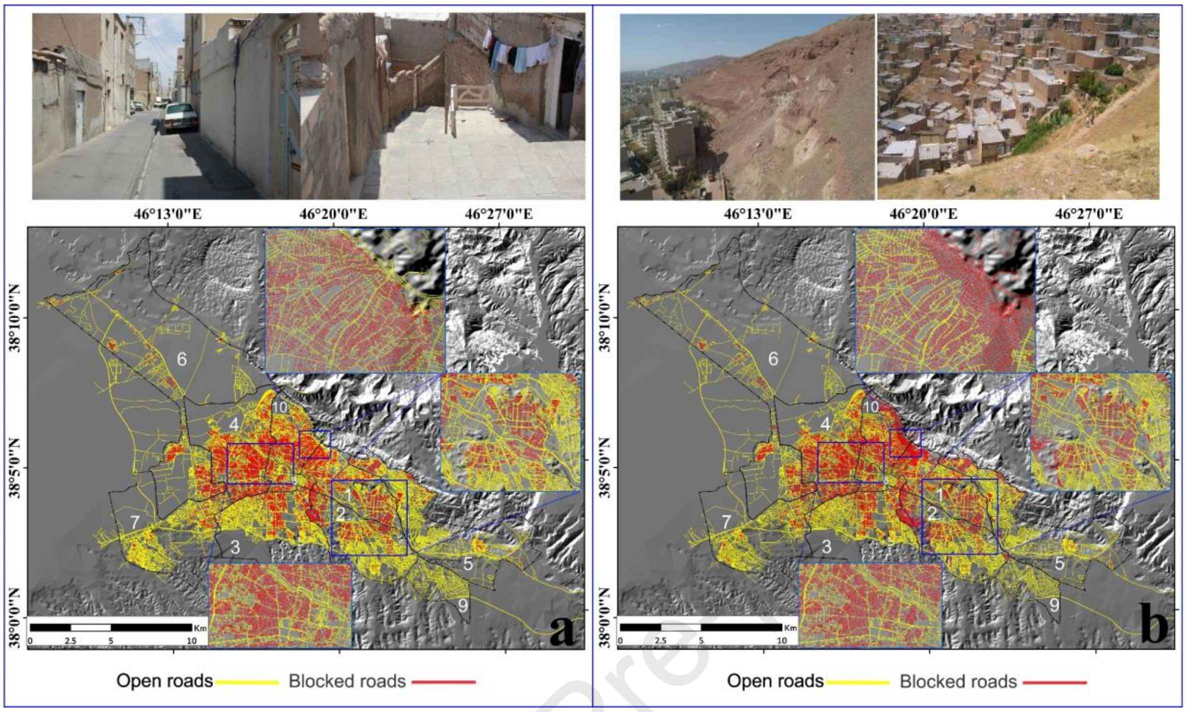

Fig. 13. a) The status of all street blockages in Tabriz city due to an earthquake, b) The status of street blockages after a landslide scenario, indicating an increase in street blockages.

As previously mentioned, Tabriz is a mountainous city situated near an active fault line. In the event of an earthquake, the movement of loose rocks and soil can have significant repercussions on infrastructure, particularly roads. The North Tabriz Highway, which serves as the primary access route to the northern part of the city, is particularly vulnerable to landslides. Such events can cause blockages that extend well beyond the highway itself, severely hindering access to northern areas of Tabriz, which have experienced the most damage and urgently require rescue and relief efforts.

The results indicating changes in street blockages due to building destruction suggest that rescue and relief operations will need to adapt significantly across many areas of Tabriz. Crisis management authorities can take proactive measures to identify sustainable solutions. Generally, following a landslide, a substantial portion of the roads may become temporarily inaccessible for rescue operations, with blockages primarily affecting main streets and complicating relief efforts.

District 2 of Tabriz is another area that has experienced notable changes, particularly in its western section, where steep slopes have led to blockages on multiple routes. The impact of landslides can also be observed in other districts. Overall, road blockages have increased by 8%, predominantly affecting main thoroughfares (see Figure 13b).

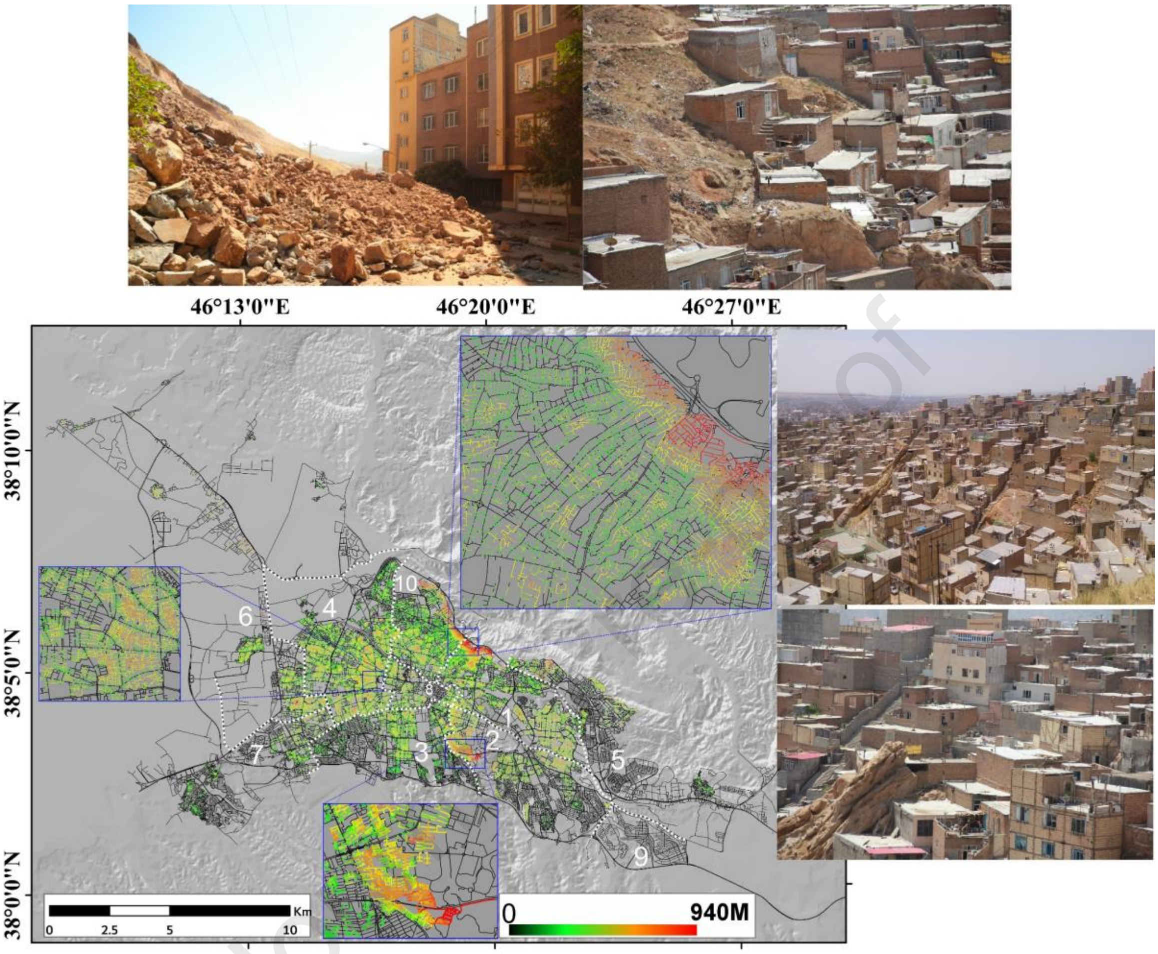

Figure 14. Distance from each blocked building to the nearest accessible road due to earthquake and landslides.

The term "vulnerability unit" refers to buildings that have sustained damage following the earthquake. The debris from these buildings obstructs roadways, while landslides further exacerbate road damage. We examined the extent of road blockages and calculated the distance from each trapped building to the nearest open road to prioritize the deployment of rescue teams and the reopening of routes for rescue operations.

As illustrated in Figure 14, the northern part of Tabriz has the longest distances to open roads. Given that residents in these areas are highly vulnerable and the population density is significant, evident from sample images of the marginal areas in District 1, many of these locations remain blocked even under stable conditions. Certain areas lack vehicular access altogether, with distances being steep and convoluted. The rate of building destruction exceeds 80% per day, and this figure is expected to rise, necessitating immediate rescue efforts and road clearance.

The total length of blocked roads requiring complete reopening is 1,560 km, with most of this distance concentrated in suburban areas, where blockages exceed 500 meters in some cases and even reach more than 900 meters. On average, blocked buildings are located just 25 meters from open roads. The northern part of Tabriz faces the most severe conditions, while the southern part is in the most favourable state. Overall, Districts 1, 4, and 10 are prioritized for road reopening.

This level of debris presents a humanitarian crisis for a developing country. We have established a target response time of 15 minutes to rescue individuals trapped under the debris each day. However, based on current conditions, the prospects for effective rescue operations in Districts 1, 4, and 10 appear bleak. As time passes, victims who are either trapped under the rubble or exposed to the elements will encounter increasingly dire circumstances, including a lack of rescue efforts, first aid, and water, which could lead to fatalities. The longer it takes to initiate rescue operations, the greater the number of victims buried beneath the debris.

3.5. Population vulnerability

Population vulnerability will fluctuate based on mortality rates during both day and night, as indicated by JICA studies [46]. Generally, vulnerability significantly increases at night. The mortality level varies according to the extent of destruction. During the night, an estimated 322,280 individuals—representing 17% of Tabriz's population—are projected to perish, with this number rising in the absence of effective rescue and relief efforts.

Table 5 presents the mortality rates, indicating that 802,087 individuals (43% of the city's population) could be rescued at night, making their assistance vital for those trapped under the rubble. This figure includes those who require immediate rescue and relief, comprising 16% of the vulnerable population. These at-risk groups are primarily situated in the northern and peripheral areas of Tabriz. Figure 15 illustrates the mortality rates during both day and night.

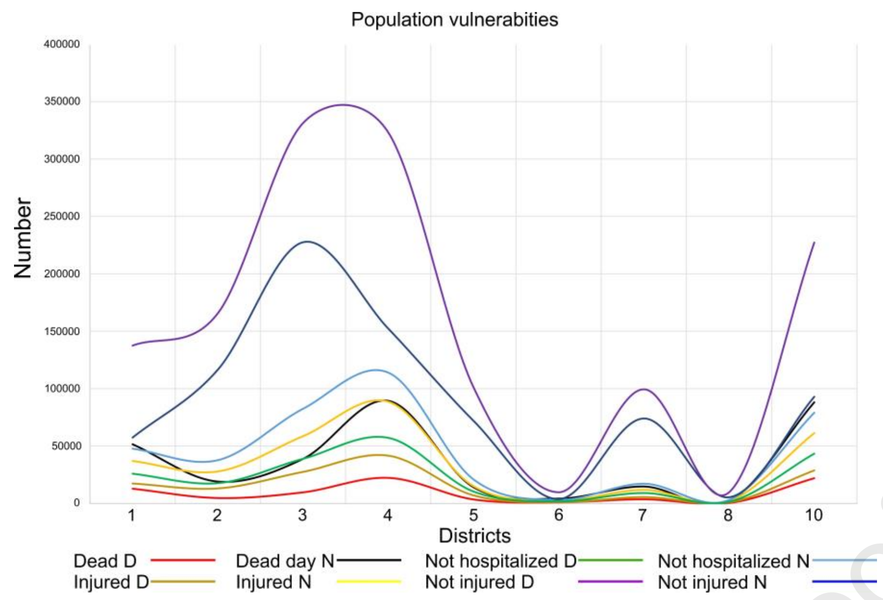

Figure 15. Casualties resulting from a 7.2 Richter earthquake, correlated with building destruction.

According to Figure 15, if an earthquake occurs at night, approximately 90,000 people will be affected in Districts 4 and 10; if it occurs during the day, this number drops to around 18,000. District 10 faces particularly challenging rescue conditions due to high levels of obstruction and the distance of each house from the nearest accessible route. In contrast, Districts 3 and 7 have the highest number of survivors, who can provide significant support during rescue operations. With open pathways, these districts are the most suitable for such efforts. District 3, with a population nearing 35,000, is poised to play a crucial role in rescue efforts.

In District 1, especially in the northern regions (marginal areas), the death rate is elevated due to poorly constructed buildings situated near the fault line and on steep slopes, making rescue operations difficult due to poor communication and access. The lack of open and safe spaces further exacerbates the situation. District 9 was excluded from the study due to its status as a newly established area with a very small population.

4. Discussion

An earthquake has destructive effects on a city, encompassing social, economic, physical, and psychological impacts. While remote sensing is highly effective in identifying post-earthquake damages, less developed countries face challenges in utilising high-resolution satellite images and advanced algorithms. In contrast, GIS have proven effective at designing prediction and scenario systems, as demonstrated in the Bam and Sarpol-e Zahab earthquakes.

Previous studies [24, 36, 37, 39] primarily focused on earthquake risk, building destruction impacts, and projected death rates. In our study, however, we examine the effects of building destruction on route blockages, not just for local roads but for all routes throughout the city. We assess the extent to which relief forces encounter roadblocks from their starting points to critical areas and whether alternative routes are available. This research demonstrates that relief forces positioned on the nearest routes may be unable to access affected areas due to obstructions, while those stationed farther away may still be able to respond.

Moreover, our study highlights the impact of landslides on road accessibility, emphasising the significance of determining the distance from each structure to the nearest accessible road—a calculation that can be made automatically. It reveals that a significant vulnerable population is affected by earthquakes, with these areas also susceptible to post-earthquake landslides. Many residents belong to vulnerable groups characterised by low educational levels, low incomes, and a high number of children, making it nearly impossible for them to rebuild their lives without global assistance. This support will be vital for improving their mental and psychological well-being, as they lack the means to construct housing and will face conditions worse than before.

In Districts 1 and 10, most structures are weakly built from low-quality materials, and the narrow passageways often prohibit vehicle access. These districts are situated on loose and unstable ground close to the Tabriz fault line. Following the earthquake, secondary access roads in these areas have become increasingly neglected and are at high risk of further earthquakes and landslides. Conversely, the eastern part of District 1 is a prosperous area with a highly educated population and higher incomes, which could facilitate rebuilding efforts. However, this area is not ideally located geologically, as it lies in close proximity to the main fault line and is also at risk of landslides. Additionally, the altitude of the buildings exceeds allowable limits, significantly impeding effective emergency response. Meanwhile, the structures in District 5 have demonstrated resilience due to their recent construction; however, being located in the northern part of Tabriz—an area prone to landslides—poses a threat to both main and secondary roads.

The density of hospitals in Tabriz is predominantly concentrated in the city centre, with districts 1, 4, 5, 8, and 10 identified as the most critical areas following an earthquake and subsequent landslides. Access to these districts will be challenging due to prolonged blockages, which can be attributed to negligence from relevant organisations and local residents. Districts 1, 5, and 10 are particularly vulnerable to landslides, leading to a significant increase in blocked buildings and trapped individuals. Following the earthquake, all buildings in Tabriz were assessed for their distance from the nearest accessible route. Alarmingly, these districts also have the highest population growth rates and a significant number of children, who are particularly vulnerable during earthquakes.

The findings indicate that the most disadvantaged social class in Tabriz will face the most severe disaster, as there is insufficient open space to accommodate the large population, and the nearest hospital will struggle to manage the influx of casualties alone. These districts will require assistance from national and potentially international aid to facilitate the relocation of their populations.

District 5 is a developed urban area that has been constructed contrary to sustainable development principles and is situated in highly unsuitable locations, making it susceptible to significant earthquake damage and extensive landslides. District 8, known for its historical significance, contains the world's largest covered market/bazaar, which is likely to suffer severe damage. Rescue operations in this area will be particularly challenging, as the use of heavy machinery will be limited. The destruction of this UNESCO World Heritage site would be catastrophic, particularly as many of its streets are only 2 meters wide and the buildings are in a deteriorating state.

Conversely, District 2 benefits from better natural conditions and is less affected by earthquakes. However, areas with poor building conditions are likely to face substantial destruction. Although developed regions may experience less damage, they could still face access blockages following landslides. In these districts, steep slopes and unstable conditions, high-rise construction instead of suitable vegetation cover, have led to become vulnerable areas. The presence of an affluent population has also resulted in the development of buildings in unsuitable areas. While these locations may appear suitable for temporary housing, they are heavily affected by landslides, posing significant risks to human lives. The city of Tabriz does have a large stadium that could be repurposed for temporary housing.

The results reveal that, should an earthquake occur, the city would experience serious damage and challenges for relief efforts. It is recommended that fundamental revisions be made to construction methods, including preventing new developments around fault lines, reinforcing structures in critical areas, preparing maps of emergency evacuation routes based on existing scenarios, and increasing public awareness and preparedness. This study can inform large-scale plans for critical areas, including creating walls/dams to prevent landslides from the northern mountain sides. Vulnerable populations, particularly the elderly and children concentrated in high-risk areas, need training to navigate crises, understand critical routes, and identify safe locations.

Improving the quality of life and living conditions in these areas is a national priority, and government support is essential for enhancing housing and widening streets. While a limited number of schools in vulnerable areas are resistant to earthquakes, most mosques in the city have been newly constructed to withstand seismic activity. Each neighbourhood mosque can serve as a storage location for essential equipment that can assist trapped individuals prior to the arrival of rescue forces. Training through the Red Crescent organization will be crucial, as the scale of destruction will be extensive, necessitating global solutions and coordination.

Areas that are particularly prone to landslides should not be considered for temporary settlement. City officials should prioritise locations with better accessibility and lower risk profiles for temporary housing. Our findings indicate that the southern part of Tabriz is the most suitable area for establishing temporary settlements and hospitals, whereas District 10 presents the worst conditions for temporary housing and should be developed near District 6 of Tabriz municipality.

Tabriz is a historic city that has experienced devastating earthquakes. Its natural growth has often violated sustainable development principles, leading to significant marginalisation and inadequate organisation. Developed areas are situated in districts that will likely suffer extensive destruction. Urban green spaces have been sacrificed for construction, and human activities near faults and steep slopes have exacerbated the risk of landslides. The city's gas network, located beneath urban structures, further heightens these risks, contributing to the potential humanitarian crisis Tabriz may face in the event of an earthquake.

Currently, Tabriz has 36 hospitals, each offering various specialties. However, given their limited capacity compared to the expected number of casualties, establishing mobile hospitals in crisis areas prone to earthquakes and landslides is essential. The northern parts of Tabriz, especially districts 1, 4, and 10, will face challenges in setting up mobile hospitals due to the dense urban fabric and lack of available space. In contrast, the southern areas of Tabriz boast ample open and green spaces, including football stadiums and large parks, which could accommodate a significant population.

Districts 2 and 3 of Tabriz municipality have the highest ratios of urban green spaces, whereas districts 10 and 8 have the least. The results highlight that using basic or low-tech mechanical rescue tools will be extremely challenging, and the high population density will result in a significant number of casualties. Rescue and relief managers should consider aerial operations, modern technologies, and international assistance as primary strategies. Furthermore, mosques could serve as temporary housing locations while fulfilling their religious roles at the neighbourhood level.

The necessary facilities and equipment for providing initial aid to injured individuals were identified, though the potential increase in casualties was not fully accounted for. Delays in rescue and relief efforts could reduce the number of healthy individuals available to assist, necessitating additional resources. The required facilities for such a scenario, as outlined in the JICA report (Table 6), were taken into consideration. In the event of a major earthquake in Tabriz, with the level of destruction anticipated, immediate social support services will be essential

704 to maintain the morale of unaffected individuals. Concurrently, there is a pressing need for aerial capabilities to
705 provide assistance to northern areas of Tabriz.

706

707 Table 6. Formulas for estimating resource requirements based on historical earthquake data [37].

Material	The formula
Total Damaged Population (TDP)	Total population-Dead people
Rescuer	(Hospitalized injuries + Injures and not hospitalized)/10
Shovel	Rescuer + Not injured people
Emergency toilet	TDP/20
Emergency bath	TDP/20
Stick and athel	(Hospitalized injuries + Injured and not hospitalized) x 10
Bandage	(Hospitalized injuries + Injured and not hospitalized) x 10
Field hospital	Hospitalized injuries/100
Drinking water (bottle per day)	3 x TDP
Canned food (per day)	1 x TDP
Bread (Loaves per day)	1 x TDP
Blanket	1 x TDP
Tent	1 x Family in need

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709

710 Table 7. Essential facilities for a nighttime scenario of a 7.3 magnitude earthquake (derived from Table 2).

Material	Number
Total Damaged Population (TDP)	1,520,624
Rescuer	345,974
Shovel	1,513,135
Emergency toilet	7631
Emergency bath	1748875
Stick and athel	4,361,781
Bandage	4,361,781
Field hospital	3,054

Drinking water (bottle per day)	4561872
Canned food (per day)	1520624
Bread (Loaves per day)	1520624
Blanket	1520624
Tent	614301

According to Table 7, providing assistance necessitates a considerable amount of equipment, and the distribution process may be time-consuming. Therefore, it is recommended that responsible individuals prepare appropriate warehouses, taking into account population density and suitable locations. Identifying distribution points will also facilitate better organisation of aid efforts. Vulnerable groups, particularly children and those who have experienced psychological trauma, should be prioritised in these assistance initiatives.

The affected areas, especially the eastern part of District 1 where reinforced concrete structures is prevalent, may encounter challenges in road clearance, as traditional methods such as shovels and wheelbarrows may prove insufficient. Similarly, areas on the outskirts, characterised by a high volume of construction debris, will require more advanced road clearance equipment.

5. Conclusions

This study undertook a comprehensive multi-hazard analysis for Tabriz, employing a historical earthquake scenario and a GIS-based hazard model. By integrating demographic, structural, and seismic risk maps, the research identified the extent of structural damage, road blockages, and landslide-prone zones. For the first time, the study quantified the combined impact of landslides and structural collapse on road blockages, conducted a post-disaster accessibility analysis, and assessed the city's resilience to multi-hazard crises.

Our findings reveal that unauthorized constructions, non-compliance with urban planning principles, and development in fault zones significantly increase vulnerability, particularly for children and the elderly in economically disadvantaged areas. The study highlights the urgent need for targeted disaster preparedness, urban planning reforms, and improved resource allocation for emergency response.

The insights provided by this research are pivotal for city managers in formulating actionable strategies to reduce mortality and enhance rescue operations. Raising community awareness and resilience is particularly critical for vulnerable populations in the suburbs of Tabriz. However, the study faced limitations due to incomplete or inaccurate data, a common challenge in developing countries. Addressing these data gaps is vital for more precise risk assessments.

For future research, the impact of road loss on evacuation should be examined in greater depth, with a dedicated study providing precise quantitative results. This is a crucial aspect of emergency response, requiring detailed discussions and actionable recommendations to improve evacuation strategies during multi-hazard events. Moreover, future studies should focus on integrating key infrastructure networks—such as water, sewage, and power transmission—into the hazard model. The application of deep learning methods could further refine risk predictions by reducing human error and increasing model accuracy, making the system more intelligent and responsive to real-time disaster scenarios.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used in this analysis is subject to confidentiality.

Acknowledgment

During the preparation of this work the author(s) used ChatGPT in order to improve language, readability and proofreading. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: