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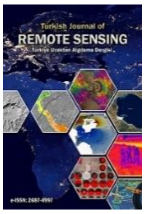

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Measuring the Vulnerability of the Urban Fabric in the Face of Land Subsidence (Case Study: District 17 of Tehran)

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Keywords
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ABSTRACT

The involvement of the 17th district of Tehran with the issue of land subsidence was the initial idea of the current research. The current research was conducted in the form of an analytical model in four steps. In the first step, after studying the research literature, the vulnerability indicators of the urban fabric were identified and organized into three criteria (physical and demographic, accessibility and proximity to high risk centers). In the second step, by using Delphi questionnaires and pairwise statistical comparisons, the priorities of vulnerability of the urban fabric in the face of land subsidence were determined. In the third step, the analytical model was defined based on the network analysis process (ANP). Also, the weight of each of the sub-criteria and criteria was obtained using Super Decision software. Finally, in the fourth step, these weights were applied to each of the layers related to the criteria in the ArcGIS software environment, and the final map of the vulnerability of the urban fabric was obtained as a raster in the geographic information system. The results of the model implementation showed that the urban fabric of the 17th district is prone to high vulnerability due to features such as high population and building density, the presence of worn-out fabric, buildings with low structural strength and very low construction quality. In total, about 657 hectares (80%) of the total built-up lands of Tehran's 17th district are under the influence of land subsidence.

Arazi çökmesi karşısında kentsel dokunun kırılganlığının ölçülmesi (Örnek olay: Tahran'ın 17. Bölgesi)

Anahtar Kelimeler:
Zemin çökmesi
Kentsel bağlam
Hasar görebilirlik
Ağ analizi (ANP)
Tahran'ın 17. bölgesi

ÖZ

Tahran'ın 17. bölgesinin arazi çökmesi sorununa dahil edilmesi, mevcut araştırmanın ilk fikriydi. Mevcut araştırma analitik model şeklinde dört adımda gerçekleştirilmiştir. İlk adımda, araştırma literatürü incelendikten sonra, kentsel bağlamın savunmasızlık göstergeleri belirlendi ve üç kriter (fiziksel ve demografik, erişilebilirlik ve yüksek riskli merkezlere yakınlık) halinde düzenlendi. İkinci adımda, Delphi anketleri ve ikili istatistiksel karşılaştırmalar kullanılarak, arazi çökmesi karşısında kentsel dokunun kırılganlığının öncelikleri belirlendi. Üçüncü adımda, ağ analiz sürecine (ANP) dayalı olarak analitik model tanımlanmıştır. Ayrıca Super Decision yazılımı kullanılarak her bir alt kriter ve kriterin ağırlığı elde edilmiştir. Son olarak dördüncü adımda, bu ağırlıklar ArcGIS yazılım ortamında kriterlere ilişkin katmanların her birine uygulanmış ve kentsel bağlamın nihai etkilenebilirlik haritası coğrafi bilgi sisteminde raster olarak elde edilmiştir. Model uygulamasının sonuçları, 17. bölgenin kentsel dokusunun, yüksek nüfus ve bina yoğunluğu, yıpranmış doku varlığı, düşük yapısal dayanıklılığa sahip binalar ve çok düşük inşaat kalitesi gibi özelliklerden dolayı yüksek hassasiyete eğilimli olduğunu göstermiştir. Toplamda, Tahran'ın 17. bölgesindeki meskun arazinin yaklaşık 657 hektarı (yüzde 80'i) arazi çökmesinin etkisi altındadır.

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1. INTRODUCTION

Urban vulnerability analysis is the evaluation and prediction of the probability of life, material and spiritual damage to the city and its residents against possible natural and unnatural hazards (Patton & Fohnston, 2001; Recchia, 2008; Karashima et al., 2014). In general, there are different types of vulnerability that are divided into four main categories: physical, social, economic and environmental (Ahsan & Warner, 2014; Kim & Marcouiller, 2015). Vulnerability is also classified in two spectrums, natural and man-made, based on the origin of the incident (Sennewald & Bailie, 2015). In this regard, land subsidence is the slow sinking of the earth's surface as a result of natural factors or human activities (Corapcioglu, 1984). Even if described as a moderate and gradual geological process that rarely causes casualties, land subsidence can be responsible for significant economic losses in urban areas (Wu et al., 2009). This issue reaches a new level of influence in the conditions of climate change, which is characterized by severe drought and rising sea levels (IPCC, 2013; Vousdoukas et al., 2017).

Land subsidence is a phenomenon that has been identified and monitored in many countries (Baer et al., 2002; Closson et al., 2005; Fares & Rana, 2005; Paine et al., 2009; Casu, 2009; Castaneda et al., 2009; Osmanoğlu et al., 2011; Chaussard et al., 2013; Liu et al., 2014; Qu et al., 2014; Üstün et al., 2015; Yalvac, 2020; Karimzadeh & Matsuoka, 2020) and has left numerous negative effects on structures, facilities and vital arteries (Galloway & Burbey, 2011; Tung & Hu, 2012; Chaussard et al., 2013; Brown & Nicholls, 2015; Corbau et al., 2019; Orhan et al., 2021). Research results show that subsidence threatens more than 12 million square kilometers (80%) of the earth's surface in the world with a probability of more than 50%. Out of 7343 big cities in the world, about 1596 big cities (22 percent) are located in potential land subsidence areas. Also, 19% of the world's population is at risk from subsidence (Garcia et al., 2021). Many countries and cities (For example, the subsidence rate in Tehran/Iran (25 cm), Yunlin/China (10 cm), Mexico City (9 cm), California/USA (7 cm), Bologna/Italy (4 cm) and Karapinar/Turkey (7 cm)) suffer from subsidence of the earth in the amount of tens of centimeters per year.

Land subsidence is probably one of the most visible environmental effects of groundwater pumping. Globally, the demand for fresh water is the main cause of this phenomenon (Oruji et al., 2019; Poland, 1984; Amelung et al., 1999; Mayoral et al., 2019). Land subsidence caused by the drainage of the aquifer system can reach total values of up to 14.5 meters (Guzy & Malinowska, 2020). Land subsidence is characterized by slow movements that usually cover large areas and include agricultural and economic activities, as well as buildings, cultural heritage and linear infrastructure, which cause significant economic losses (Ezquerro et al., 2020). Geological disasters caused by surface deformation are common, especially in urban areas, which seriously hinder the sustainable development of urbanization. Monitoring and analysis with high spatial and temporal resolution is especially important for assessing the risk of geological disasters caused by urban transformation (Hu et al., 2022). Land subsidence has harmful consequences on the constructions on the soil and the vital arteries buried in the soil. If the process of withdrawing water from an aquifer continues, this phenomenon can cause the loss of the efficiency of structures and vital arteries, and the result will be a crisis in the region (Baum et al., 2008; Bott et al., 2021). The effect of land subsidence can be seen mainly from four aspects: 1) Damage to infrastructure, e.g. pipelines, buildings and dams; 2) Reducing the serviceability of roads and railways due to the deformation of the road surface and railway foundations (Chen et al., 2020); 3) Increased flood exposure (Du et al., 2018); and 4) It may become a channel for the penetration of ground pollution sources into underground sources and cause groundwater pollution (Hussain & Abed, 2019; Zhang, 2019). Despite the studies conducted on land subsidence issues, many studies have not been conducted on the effect of land subsidence on the urban fabric and its components (Table 1). For this reason, it is felt necessary to deal with the effect of land subsidence on the urban fabric - which can endanger the lives of millions of people - in order to better understand the effect of this phenomenon.

Due to the uncontrolled extraction of groundwater, Iran is currently one of the countries with the highest annual subsidence rate (25 cm of subsidence per year) (Garcia et al., 2021). Excessive extraction of water from underground aquifers during decades for agricultural and industrial purposes has caused severe land subsidence in many plains of Iran (such as Marand plain (Roustaei & NajafVand, 2022), Ardabil plain (Abedini et al., 2022), Kashan plain (Saqazadeh et al., 2022), central plain of Qain city (Hosseinzadeh et al., 2022), Hashtgerd plain (Mehrnour et al., 2022), Sarab plain (Asghari Saraskanroud et al., 2022), Isfahan (Azarm et al., 2022), Hamedan urban area (Ganjaian et al., 2022), Qara Balag plain of Fars Province (Yamani et al., 2009), Rafsanjan plain (Motagh et al., 2017), Neyshabour (Dehghani et al., 2009), Tehran plain (Azadnejad et al., 2020), Qazvin plain (Babaei et al., 2020) and Neishabor plain (Rezaei et al., 2020)). In the meantime, the southwest plain of Tehran is one of the areas that is facing a decrease in the level of underground water, and as a result, signs of subsidence can be seen in this area (Mahmoudpour et al., 2016; Country Mapping Organization, 2018) and this issue is a serious threat to the urban and industrial fabric and body as well as the agricultural lands of this region. In this regard, district 17 of Tehran is one of the areas where land subsidence has occurred (SharifiKia et al., 2013) and is subsiding at a rate of 1 to 25 cm (Karimi et al., 2014; Country Mapping Organization, 2018). The possibility of simultaneous subsidence with an earthquake due to the proximity of the 17th region to the active Ray fault (as a trigger for landslides) makes this region susceptible to a severe disaster with high human casualties. Therefore, the main goal of this research is to measure the vulnerability of the urban fabric in the face of land subsidence, and to achieve this goal, the urban fabric of the 17th district of Tehran has been selected. The tools used in this research to measure the vulnerability of the urban fabric are network analysis (ANP) and GIS.

Table 1. Some studies done in relation to land subsidence

Researchers	The subject of research
Pratt and Johnson	First observation of subsidence associated with subsurface processes (Pratt and Johnson, 1926)
Terzaghi, 1923	The first milestone in the theory of aquifer consolidation due to groundwater pumping (Gambolati et al., 2015)
Gambolati and Freeze	The first mathematical modeling of subsidence (Gambolati et al., 2015)
Poland	Acceptance of concepts related to land subsidence and water harvesting thanks to the substantial contributions of Polland (Poland, 1958, 1960, 1961; Poland and Davis, 1956, 1969; Poland et al., 1959; Poland and Green, 1962)
Feth, 1949	Observation of ground ruptures related to ground subsidence (Holzer and Davis, 1976; Holzer et al., 1979)
Holzer and Pampeyan	Holzer and Pampian recognized that fissures were caused by human factors (Jachens and Holzer, 1979; Holzer and Pampeyan, 1981; Jachens and Holzer, 1982)
Baum et al.	Loss of efficiency of vital structures and arteries under the influence of land subsidence (Baum et al, 2008)
Gutierrez et al.	Investigating the impact of subsidence on a building with 100 apartments using geophysics and trenching techniques (Gutierrez et al., 2009)
Chaussard et al.	Heavy rains associated with monsoon and tropical storms, lack of coastal or river defenses, as well as limited evacuation potential, increase the vulnerability of Indonesian cities to land subsidence (Castellazzi et al., 2013)
Castellazzi et al.	Correspondence between recent changes in subsidence rate with geological data in large cities of central Mexico (Castellazzi et al, .2016)
Herrera Leon et al.	Investigating the relationship between natural factors and human factors as the causes of subsidence (Herrera Leon et al., 2018)
Oruji et al.	The most important reason for land subsidence is excessive extraction of underground water tables (Oruji et al., 2019)
Aslan et al.	Correlation between subsidence and changes in groundwater depth (Aslan et al., 2019)
Ciampalini et al.	Subsidence analysis of a recently built cargo terminal (Guasticce Terminal) in the Tuscany region (Central Italy) (Ciampalini et al., 2019)
Ezquerro et al.	Assessing the vulnerability of buildings due to ground subsidence in the historic city of Pistoia, Italy (Ezquerro et al, 2020)
Orhan et al.	Correlation between subsidence and changes in groundwater depth (Orhan et al., 2021)
Garcia et al.	Mapping the global threat of land subsidence (Garcia et al., 2021)

2. THE STUDY AREA

District 17, as one of the 22 districts in the southwest of Tehran metropolis (Figure 1), is located on the bed of its alluvial plain. With an area of 824 hectares (equivalent to 1.15% of the total land of Tehran's legal boundaries), this area is the smallest and densest area of Tehran after area 10, which has 3 districts and 14 neighborhoods (Azizzadeh et al., 2016). The population of the region in 2022 is 278,354 people with a net population density of 668 people per hectare. District 17 is referred to as the densest district of Tehran (having a population density four times that of other districts). Desolation (weariness of 70% of buildings) and severe density, unstable and irregular urban fabric, severe interference of uses, irregular street construction and nested alleys with narrow and long passages and heavy traffic of vehicles are among the distinctive features of this area (Table 2).

Table 2. Characteristics of district 17 of Tehran city

Characteristics	District 17	Percent
Area	824 hectares	100
The area of built up land	774 hectares	94
Residential area	417 hectares	54
Area of worn tissue	684 hectares	88
Population	278354	

Region 17 is affected by three faults north of Tehran, south and north of Ray, and from this point of view, it is considered one of the most vulnerable areas of Tehran in dealing with accidents caused by earthquakes. The lands of this region are located on a bed of stones resulting from the aggregation of volcanic rocks, which consists of sedimentary alluvium of Tehran lands and clay forms a major part of it (Asgari et al., 2002: Site of Region 17 of Tehran Municipality, 2002).

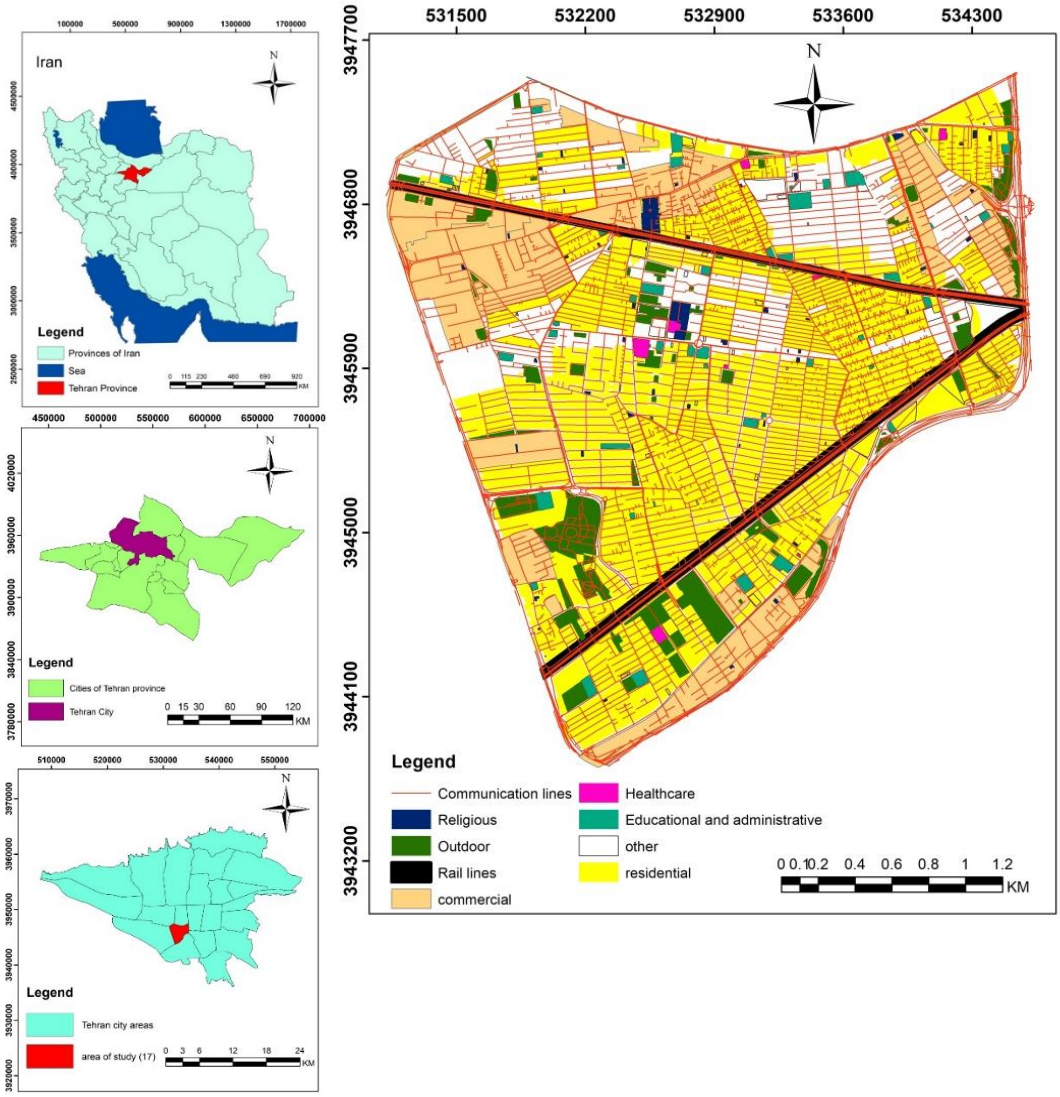

Figure 1. Geographical location of district 17 of Tehran city

3. METHODOLOGY

The purpose of this research is to measure the vulnerability of the urban fabric of the 17th district of Tehran in the face of land subsidence, which was realized in the form of an analytical model in four steps (Figure 2). In the first step, identification and classification of vulnerability indicators of the urban fabric was done based on three physical and demographic criteria, accessibility and proximity to high risk centers by reviewing the latest research. In the second step, using a questionnaire tool and a survey of 30 experts and people knowledgeable about the research topic, the priorities of the vulnerability of the urban fabric in the face of land subsidence were determined. In the third step, the analytical model was defined based on the ANP network analysis method, and the weight of each of the sub-criteria and criteria was obtained using Super Decision software. Also, specific weights obtained from ANP modeling were applied to the spatial layers of the region. In the fourth step, these weights were applied to each of the layers related to the criteria in the ArcGIS software environment, and along with that, the layers were combined. Finally, the final urban tissue vulnerability map was obtained as a raster in the geographic information system. The process of conducting research using the combined Delphi method and network analysis (ANP) has been proposed by researchers in different ways. The basis of this research is a combination of Fowles, 1978 and Cheng Eddie, 2007 and Saaty, 2005. The basis of the Delphi method is that the opinion of the experts of each scientific field is the most correct opinion regarding the prediction of the future; Therefore, unlike survey research methods, the credibility of the Delphi method does not depend on the number of participants in the research, but on the scientific credibility of the experts participating in the research. In this study, according to the use of paired comparisons questionnaire and network analysis method and the need to use the opinions of experts, 30 university professors, crisis and unforeseen events organization, environmental organization and municipality who were highly familiar with land subsidence issues , were selected as samples by a purposeful method of judgment. For this purpose, a Delphi questionnaire and finally a pairwise comparison questionnaire were designed and distributed among experts.

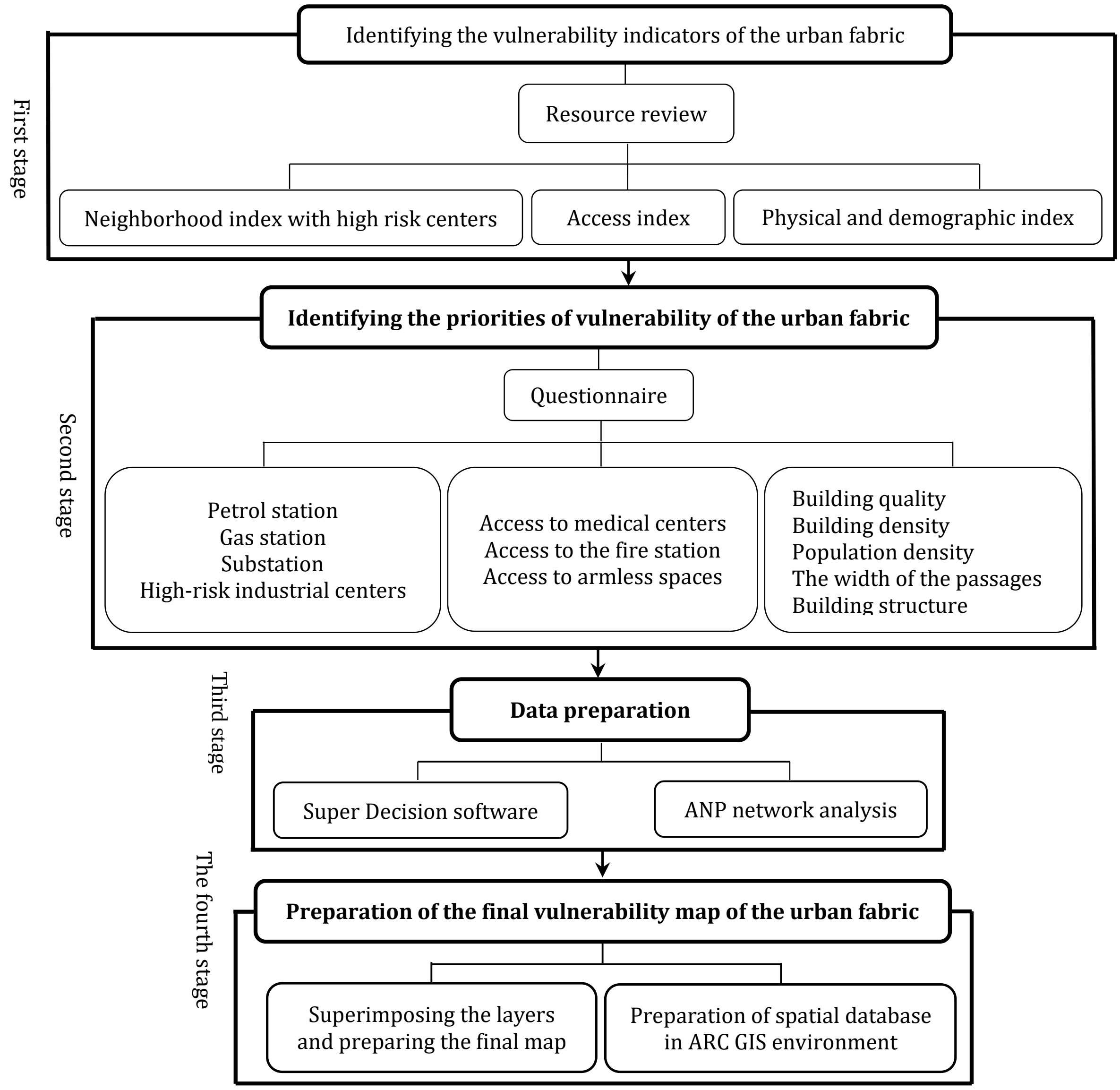

Figure 2. Analytical model for assessing the vulnerability of the urban fabric of the 17th district of Tehran in the face of land subsidence

3.1. Introducing the Criteria and Indicators for Measuring the Vulnerability of the Urban Fabric

Examining the opinions of experts in this study indicated that among the indicators considered for physical and demographic criteria, five basic indicators are 1. quality of buildings, 2. building density, 3. population density, 4. width of roads and 5. The skeleton of the building has been determined. Also, among the indicators considered for the access criteria, three basic indicators have been determined: 1. Access to medical centers, 2. Access to the fire station, and 3. Access to open and empty spaces. On the other hand, among the indicators considered for the criterion of proximity to high risk centers, four basic indicators 1. proximity to gas stations, 2. proximity to gas pumps, 3. proximity to electric substations, and 4. proximity to high-risk industrial centers were determined. (Table 3). In order to measure the level of vulnerability and within the framework of the proposed criteria, the determined indicators need to be conceptualized in order to make a quantitative judgment about measuring the level of vulnerability:

3.1.1. Quality of the building

The higher the strength of the building and the more durable materials it is made of, the less vulnerable it will be (Ahdanjadrosheni et al., 2014; Tavakoli & Akbarpour, 2010; Siyami et al., 2013). The quality of buildings and their construction is one of the factors affecting the resistance of urban buildings against the pressures. From this point of view, urban buildings can be divided into three categories: newly built, renovated and demolished (Farzamshad & Iraqizadeh, 2011; MohammadiDeh-Ceshmeh, 2012; Ebrahimian-Qajari et al., 2013).

3.1.2. Building density

It is an important indicator that increases the probability of destruction and vulnerability. By dividing the city into a grid of 250x250 meters, the grids with the number of buildings up to 75 buildings will be low vulnerability, 75-150 buildings in each grid will be medium vulnerability and 150-300 buildings will be high vulnerability (Siyami et al., 2013; Ebrahimian-Qajari et al., 2013).

Table 3. The criteria and indicators for assessing the vulnerability of the urban fabric

Criterion	Indicator	The degree of vulnerability			Source
		Low	**Mediocre**	**High**	
Physical and demographic	Building quality	Newly built	Restoration	Destructive	Tavakoli & Akbarpour, 2010 Farzamshad & Iraqizadeh, 2011 MohammadiDeh-Ceshmeh, 2012 Siyami et al., 2013 Ebrahimian-Qajari et al., 2013
	Building density	0-75	75-150	150-300	Ahadanjadroshani et al., 2014 Siyami et al., 2013 Ebrahimian-Qajari et al., 2013
	population density	Less than 100 people per hectare	100-200 people per hectare	More than 200 people per hectare	Peacock et al., 1997 Enarson & Morrow, 1998 Tierney, 2006 Habibi et al., 2008
	The width of the passages	More than 14 meters	9-14 meters	Dead end, 6-9 meters, under 6 meters	Habibi et al., 2008 Azizi & Barnafar, 2011 Siyami et al., 2013 Ebrahimian-Qajari et al., 2013 Alikhani et al., 2017
	The skeleton of the building	Concrete	Metallic	Other	Okada & Takai, 2000 Hatami-Nejad et al., 2009 Firouzi et al., 2013 Ebrahimian-Qajari et al., 2013
Access	Access to medical centers	Less than 250 meters	200-500 meters	More than 500 meters	Azizi & Barnafar, 2011 Farzamshad & Iraqizadeh, 2011 Siyami et al., 2013
	Access to the fire brigade	Less than 750 meters	750-1500 meters	More than 1500 meters	Siyami et al., 2013
	Access to open, empty spaces	Less than 250 meters	250-500 meters	More than 500 meters	Siyami et al., 2013
Adjacent to high risk centers	Petrol station	More than 150 meters	75-150 meters	Less than 75 meters	Azizi & Barnafar, 2011 Siyami et al., 2013
	Gas station	More than 100 meters	50-100 meters	Less than 50 meters	
	Electricity substation	More than 100 meters	50-100 meters	Less than 50 meters	
	Industrial centers	More than 400 meters	200-400 meters	Less than 200 meters	Research processes

3.1.3. Population density

Population density is generally considered as a factor that aggravates the vulnerability of urban tissues (Habibi et al., 2008). Obviously, with the increase in population density, vulnerability also increases (Peacock et al., 1997; Enarson & Morrow, 1998; Tierney, 2006).

3.1.4. Width of roads

The smaller the width of the road, the more likely it is to be vulnerable, because with the collapse of the debris in the roads, it becomes difficult to provide assistance. Also, the greater the width of the roads, the less the possibility of passing traffic (Habibi et al., 2008; Azizi & Barnafar, 2011; Ebrahimian-Qajari et al., 2013).

3.1.5. Building skeleton

The resistance of all types of buildings can be defined by the intensity of the incoming loads, and the vulnerability of the building is one of the main factors affecting human casualties. Therefore, analysis of building safety against accidents is a very important issue (Okada & Takai, 2000). Metal and reinforced concrete skeletons have less vulnerability than other materials, brick and stone skeletons have medium vulnerability and wooden, cement block, clay and mud skeletons have high vulnerability (Hatami-Nejad et al., 2009; Firouzi et al., 2013; Ebrahimian-Qajari et al., 2013).

3.1.6. Access to medical centers

Access to medical centers speeds up rescue operations and service delivery. In this way, by moving away from medical centers, the possibility of vulnerability increases (Azizi & Barnafar, 2011; Farzamshad & Iraqizadeh, 2011; Siyami et al., 2013).

3.1.7. Access to the fire station

Proper access to relief centers can reduce the damage caused by land subsidence (Siyami et al., 2013).

3.1.8. Access to open and empty spaces

Appropriate distribution of places that have the ability to temporarily accommodate people, reduces damage during and after an accident. These spaces include green spaces, open spaces and indoor sports halls in cities (Siyami et al., 2013).

3.1.9. Adjacent to petrol stations, gas stations and industrial centers

At the city level, fuel storage tanks, gas stations and centers that have the potential to release a lot of energy can be considered as harmful uses (Azizi & Barnafar, 2011; Siyami et al., 2013).

3.2. Hierarchical Analysis

Analytic Network Process (ANP) is a multi-criteria decision-making method that is very similar to Analytical Hierarchy Process (AHP) and in better words, it is an extended form of Analytical Hierarchy Process. The main difference between the network and hierarchical analysis methods is in the structure of the model definition and the relationship between its elements. This relationship in the hierarchical analysis method is only independent, while in the ANP method, this relationship can be both independent and dependent. This feature causes dependencies and feedbacks between criteria and sub-criteria to be systematically checked (Chung & Lee, 2005). The network analysis method considers the complex relationships between decision elements by replacing the hierarchical structure with a network structure. For this reason, in recent years, the use of ANP has increased in most fields (Zebardast, 2011). In the process of network analysis, as in the process of hierarchical analysis, the comparative spectrum of 1-9 is used. This scale of comparison enables the decision maker to intuitively unite knowledge and experience and determine how many times one element is dominant over another element in terms of criteria. The decision maker has the possibility to express his preference in the form of each pair of elements verbally, equal importance, relatively more important, more important, very important, absolutely important. In the next step, these descriptive preferences are translated into numerical values of 3, 1, 5, 7, 9 respectively. Values 4, 2, 6, 8 are also used as median values in comparison between two consecutive judgments. The reverse of these numbers is used for the other side of judgments.

As mentioned earlier, in order to measure the vulnerability of the urban fabric of the 17th district of Tehran in the face of land subsidence, after determining the indicators using the Delphi method and preparing information layers, the ANP method was applied to the data. Then, the weight of each of the sub-criteria and criteria was determined and entered into the Super Decision software (Tables 4 and 5).

Table 4. The matrix of pairwise comparisons and the weight of the main criteria

Criteria	Physical and demographic	Access	Adjacent to high risk centers	Final weight
Physical and demographic	1	7	8	0/757
Access	1/7	1	6	0/188
Adjacent to high risk centers	1/8	1/6	1	0/055

Table 5. Calculated threshold super matrix for measuring urban tissue vulnerability

		Physical and demographic criteria					Access criteria			Neighborhood criteria with high risk markers			
		Building quality	Building density	Population density	The width of the passages	The skeleton of the building	Access to medical centers	Access to the fire station	Access to open space	Petrol station	gas station	Substation	High-risk industrial centers
Physical and demographic criteria	Building quality	0/214	0/214	0/214	0/214	0/214	0/214	0/214	0/214	0/214	0/214	0/214	0/214
	Building density	0/241	0/241	0/241	0/241	0/241	0/241	0/241	0/241	0/241	0/241	0/241	0/241
	Population density	0/123	0/123	0/123	0/123	0/123	0/123	0/123	0/123	0/123	0/123	0/123	0/123
	The width of the passages	0/119	0/119	0/119	0/119	0/119	0/119	0/119	0/119	0/119	0/119	0/119	0/119
	The skeleton of the building	0/126	0/126	0/126	0/126	0/126	0/126	0/126	0/126	0/126	0/126	0/126	0/126
ccess criteria	Access to medical centers	0/051	0/051	0/051	0/051	0/051	0/051	0/051	0/051	0/051	0/051	0/051	0/051
	Access to the fire station	0/021	0/021	0/021	0/021	0/021	0/021	0/021	0/021	0/021	0/021	0/021	0/021
	Access to open space	0/044	0/044	0/044	0/044	0/044	0/044	0/044	0/044	0/044	0/044	0/044	0/044
Neighborhood criteria with high risk markers	Petrol station	0/016	0/016	0/016	0/016	0/016	0/016	0/016	0/016	0/016	0/016	0/016	0/016
	gas station	0/019	0/019	0/019	0/019	0/019	0/019	0/019	0/019	0/019	0/019	0/019	0/019
	Substation	0/011	0/011	0/011	0/011	0/011	0/011	0/011	0/011	0/011	0/011	0/011	0/011
	High-risk industrial centers	0/015	0/015	0/015	0/015	0/015	0/015	0/015	0/015	0/015	0/015	0/015	0/015

The weight obtained from ANP modeling was applied to the input layers. In the end, the final map to determine the vulnerability of residential use was obtained in the form of a grid. By examining the vulnerability assessment model, it was found that vulnerability criteria and indicators do not have the same importance. Meanwhile, the physical and demographic criterion with a weight of 0.757 has the highest value in measuring vulnerability. Also, among the analyzed indices, the building density index with a weight of 0.241, the building quality index with a weight of 0.214, the building skeleton index with a weight of 0.126, the population density index with a weight of 0.123 and the road width index with a weight of 0.119 respectively has the highest value in measuring the level of vulnerability from the point of view of experts and people aware of the issue of land subsidence.

4. RESULTS

There are 5 CNG stations in the studied area and according to the standard distance of 50 meters, about 4.19 hectares (0.54%) of the built-up lands are in the radius of high vulnerability (Figure 3).

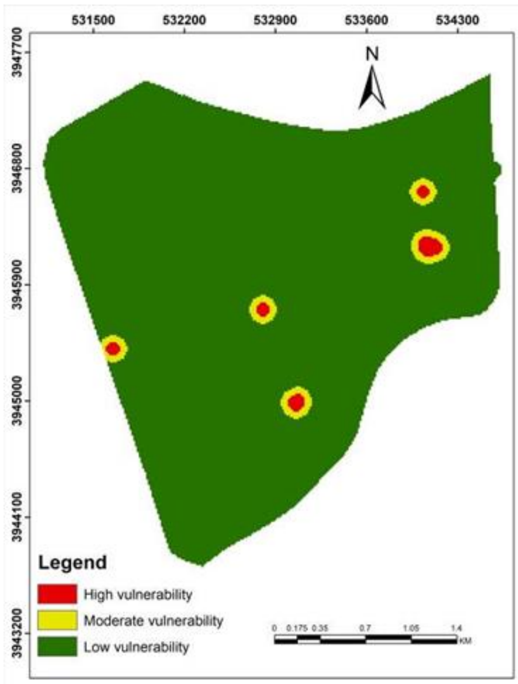

Figure 3. Vulnerability map due to CNG explosion

There are 3 petrol stations in the studied area, and according to the existing standard, the built structure that is less than 75 meters from the gas station has a high vulnerability, and according to this, about 3.5 hectares (0.68 percent) of the total built-up land area of the region are in the high vulnerability range (Figure 4).

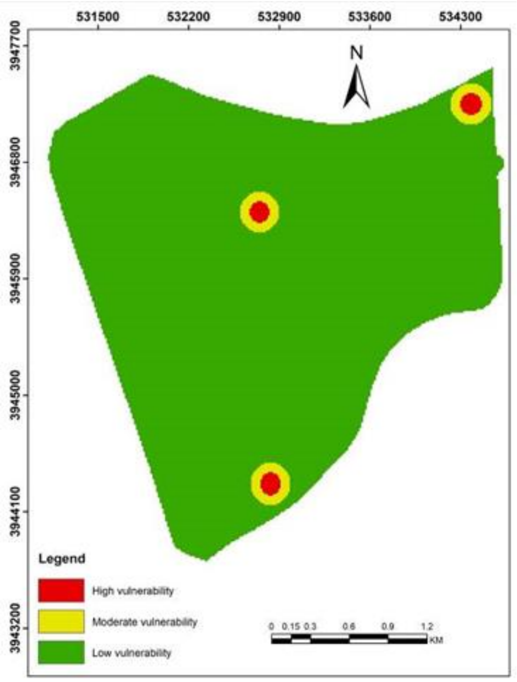

Figure 4. Vulnerability map due to petrol station explosion

There are 6 high-risk industrial centers in region 17, which according to the standards of the Ministry of Energy and Industry, about 12.57 hectares (1.62 percent) of the total built-up land area of the region are in the high vulnerability range (Figure 5).

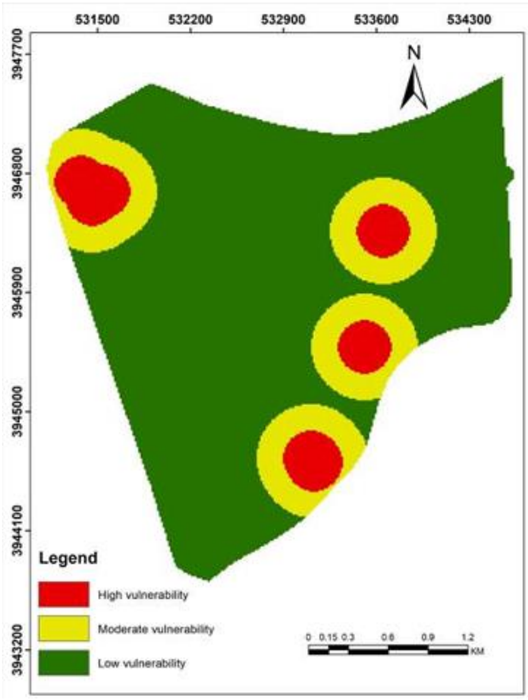

Figure 5. Vulnerability map according to the distance from high-risk industrial centers

Also, there are 79 electricity substations in the study area, which according to the 50 meter distance standard, about 62.6 hectares (8.09%) of the total built-up land area of the region is in the radius of high vulnerability (Figure 6).

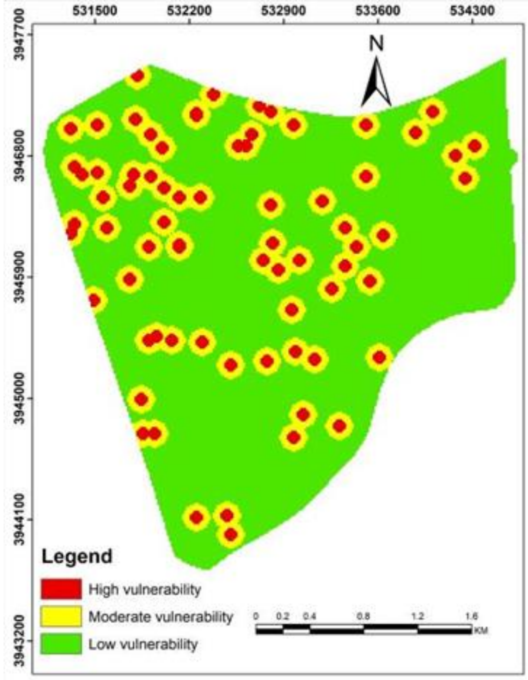

Figure 6. Vulnerability map due to the explosion of electric substations

In total, by analyzing the criteria indicators of proximity to high risk centers, it was determined that out of the total area of built-up lands in Region 17 (774 hectares), about 85 hectares (11 percent) of built-up lands are in the danger radius with high vulnerability. Based on the index of access to medical centers, a total of 262 hectares (32%) of the total area of Region 17 are outside the radius of effective access (with a distance of more than 500 meters) from medical centers (Figure 7).

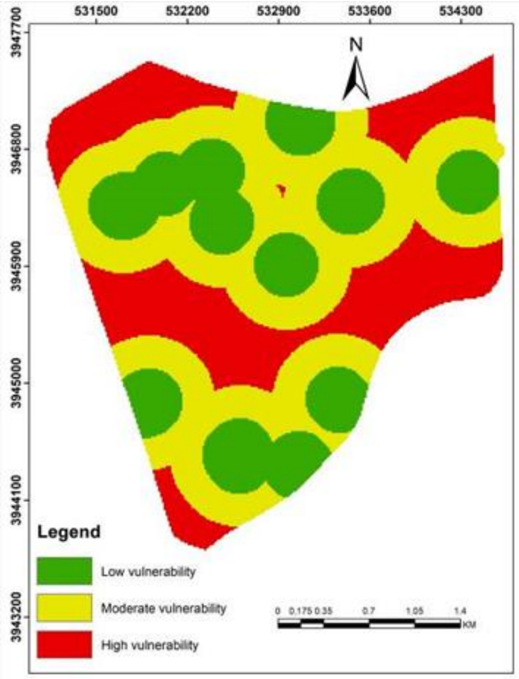

Figure 7. Vulnerability map according to access to medical centers

There have been 2 fire stations in region 17, which are located in about 114 hectares (14 percent) of the total built-up area of the region outside the effective access radius (with a distance of more than 1500 meters) from the fire station (Figure 8).

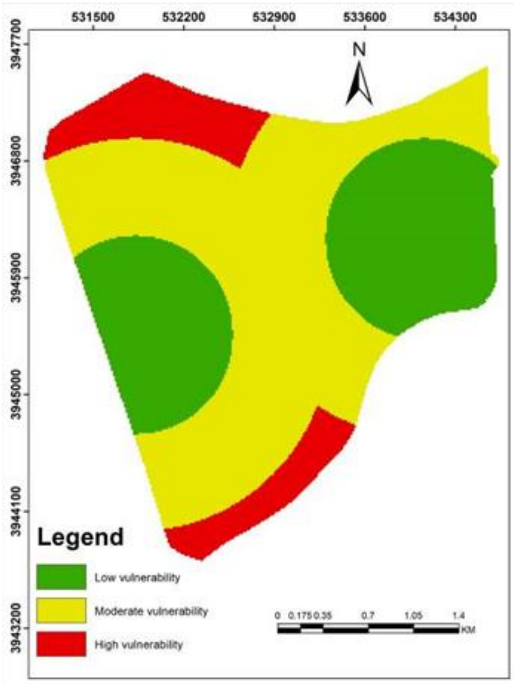

Figure 8. Vulnerability map according to access to the fire station

Access to open and empty places is another indicator that can be effective in reducing human injuries during and after a crisis. Examining this index in the studied area shows that in region 17, about 62 hectares (7.5 percent) of the entire area are outside the radius of effective access (with a distance of more than 500 meters) of open and empty spaces (Figure 9).

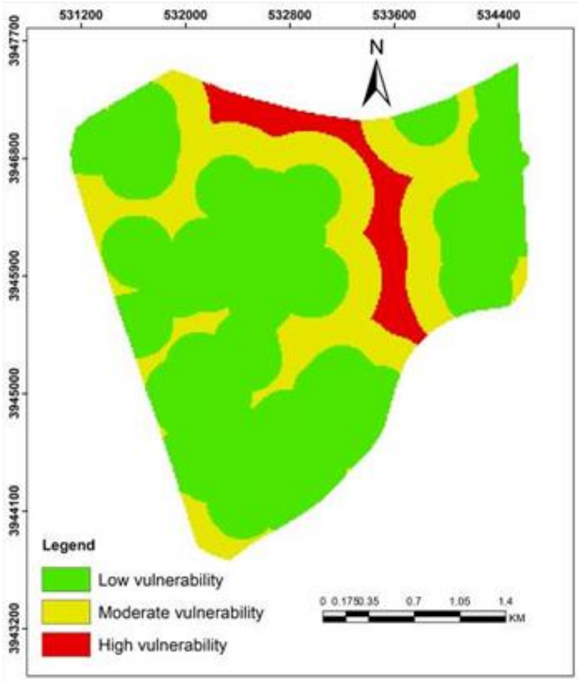

Figure 9. Vulnerability map according to access to armless spaces

By examining the building quality index in region 17, it was found that 491.2 hectares (63.4 percent) of the total built-up land have dilapidated buildings (high vulnerability) (Figure 10).

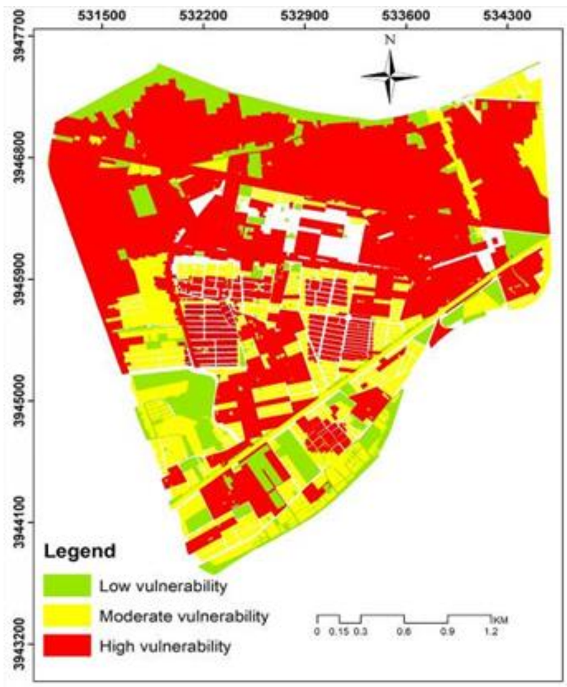

Figure 10. Vulnerability map according to building quality

The above percentages show that the vast majority of existing buildings in area 17 have a worn texture and in case of land subsidence in this area, we will witness a human disaster.

In terms of building density index, district 17 has a high building density and has a high percentage of vulnerability. Of the total area of built-up land in Region 17, about 464 hectares (60%) have high density, 52 hectares (7%) have medium density and 258 hectares (34%) have low density (Figure 11).

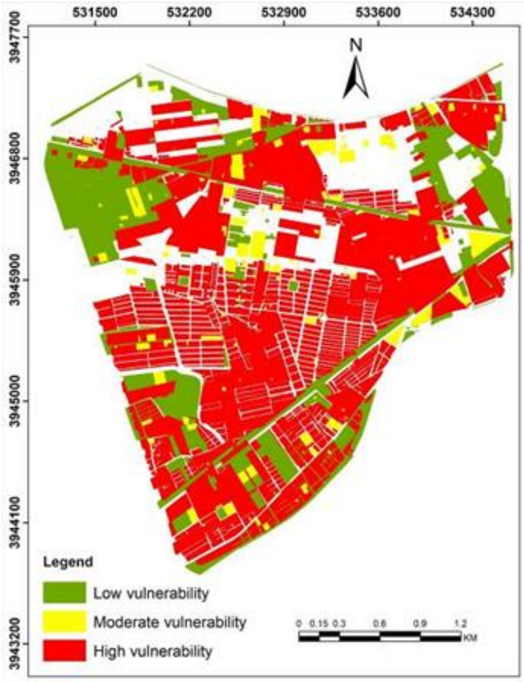

Figure 11. Vulnerability map according to building density

The road width index is an important index that will play a very important role in the event of a disaster in an area. Surveys showed that of the total area of built-up land in Region 17, 269 hectares (35%) have low vulnerability, 185 hectares (24%) have medium vulnerability, and 321 hectares (42%) have high vulnerability. The above survey shows that more than 66% of the studied area has narrow passages and no access hierarchy, and in case of land subsidence, many problems will be created for residents to escape from the danger area (Figure 12).

Figure 12. Vulnerability map according to the width of the roads

The building skeleton is another important indicator that can be effective in reducing human injuries during a crisis. Examining this index in the studied area shows that about 364 hectares (47%) of the constructed buildings have concrete skeletons, 145 hectares (19%) of the constructed buildings have iron and brick skeletons, and 267 hectares (35%) of the existing buildings have an unsustainable and weak skeleton and are highly vulnerable (Figure 13).

Figure 13. Vulnerability map according to the type of skeleton of buildings

The most influential indicator for measuring the vulnerability of urban tissue in the face of land subsidence is population density. In region 17, the population density is 668 people per hectare, and more than 161,047 people (58%) of the total residents of this region are at high risk in case of land subsidence. Excessive population density has greatly increased the vulnerability of region 17 and this region has the potential of a human and environmental disaster in case of land subsidence (Figure 14).

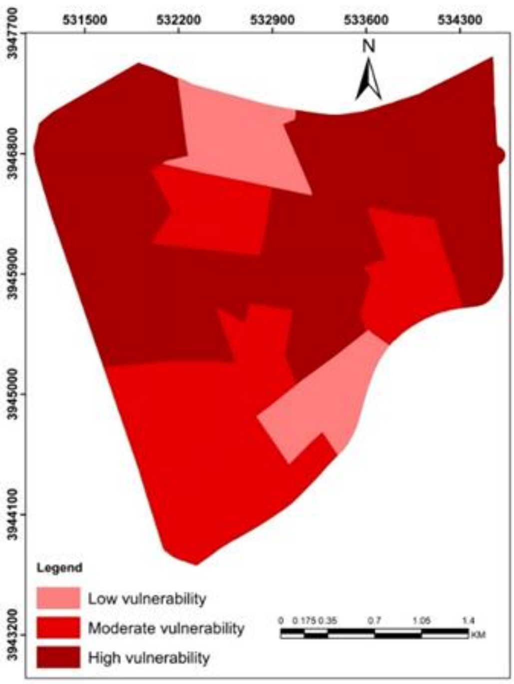

Figure 14. Vulnerability map according to population density

4.1. Combining the Layers and Preparing the Final Vulnerability Map of the 17th District of Tehran

By overlapping the vulnerability layers with area 17, the vulnerability status of this area was determined in three levels: low, medium and high. The investigations of this research showed that a high percentage of the built-up lands in the 17th region have characteristics such as worn texture, buildings with low structural strength, very low construction quality of buildings and high density of buildings and population and are prone to high vulnerability. Based on this, from the total area of region 17 (824 hectares), about 166.8 hectares (20.2%) are in the low vulnerability range, 92.5 hectares (11.2%) are in the medium vulnerability range and 564.5 hectare (68.5 percent) is in the range of high vulnerability in case of land subsidence (Figure 15). In total, 657 hectares (80 percent) of the built-up lands in Region 17 are under the influence of land subsidence.

Figure 15. Vulnerability map of the urban fabric of the 17th district of Tehran in the face of land subsidence

5. CONCLUSION

The phenomenon of land subsidence affects the structure, texture and components of a city, but many studies have not been done on the effect of this phenomenon on the urban fabric. In particular, this research has used ANP network analysis and GIS software to assess the vulnerability of the urban fabric of the 17th district of Tehran in the face of land subsidence. The high population and building density, existence of dilapidated texture, buildings with low structural strength, very low construction quality of buildings, small width of passages and irregular texture and lack of access hierarchy, and the study area is involved with three earthquake faults makes it important to measure the vulnerability of the urban fabric of the 17th region in the face of land subsidence. In this research, the most effective criteria and indicators for measuring the vulnerability of urban fabric under the influence of land subsidence were introduced using the Delphi method and the ANP method. According to the analysis done in ArcGIS software, regarding the studied area, the following can be mentioned as the main issues in region 17:

- In terms of the criterion of being adjacent to high risk centers, about 85 hectares (11%) of the total built-up land area is in the danger radius with high vulnerability.
- In terms of the index of access to medical centers, about 262 hectares (32%) of the total area of the region are outside the radius of effective access.
- In terms of access index to the fire station, about 114 hectares (14%) of the total area of the region are outside the radius of effective access.
- In terms of the index of access to open and empty spaces, about 62 hectares (7.5%) of the total area

of the region are outside the radius of effective access.

- In terms of building density index, this area has a high building density and has a high percentage of vulnerability.
- In terms of road width index, 506 hectares (66 percent) of the total built-up land area of the region is highly vulnerable. This area has narrow passages and no access hierarchy, and in case of land subsidence, many problems will be created for residents to escape from the danger zone.
- According to the building skeleton index, 267 hectares (35%) of the built buildings have weak and weak skeletons and are highly vulnerable. Also, most of the concrete and metal structures are old and have low construction quality.
- In terms of the population density index, more than 161,047 people (58%) of the residents of this region are exposed to high vulnerability.
- In terms of building quality index, more than 491 hectares (63%) of the existing buildings have worn texture and have a high percentage of vulnerability.

By overlapping the layers of vulnerability with the 17th district of Tehran, the vulnerability status of the region was determined in three levels: low, medium and high. The results of this research showed that a high percentage of built-up land in this region has characteristics such as high population and construction density, the presence of worn-out texture, buildings with low structural strength, very low construction quality of buildings, small width of roads and irregular texture. Based on this, land subsidence has exposed 657 hectares (80 percent) of the lands of the 17th district of Tehran to high vulnerability. Considering the importance of the issue of land subsidence and the need for the country's crisis management authorities to address this issue, the following executive-operational solutions are suggested to prevent the possibility of a crisis:

- Injection of double frames to places with subsidence using jet grouting or micropile methods;
- The use of geosynthetics under surface foundations in order to reduce the impact of subsidence on the structure;
- Injecting and pumping water inside the ground in order to reduce the subsidence rate;
- Using flexible foundations during new constructions in areas prone to subsidence; and
- Prohibition of construction in areas with severe subsidence.

Author contributions

The authors contributed equally to the article.

Conflicts of Interest

The authors declare no conflict of interest.

Research and publication ethics statement

In the study, the authos declare that there is no violation of research and publication ethics and that the study does not require ethics committee approval.

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