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GIS-based seismic vulnerability assessment for the Istanbul Historical Peninsula

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Abstract

According to the Index of Risk Management-INFORM 2020 Report, Turkey was included in the group of "high-risk" countries in terms of humanitarian crises and disasters with an index score of 5.0 in 2019. In statistics related to the damage caused by disasters, it is known that natural disasters cause a 3% loss in Turkey's gross national product every year, and this rate approaches 4-5% with indirect losses. Since disasters cause socioeconomic, physical, and institutional losses, attention has been given to the importance of disaster management and risk reduction studies. This paper focuses on vulnerability assessments and presents a multi-criteria decision-making and earthquake-related vulnerability assessment method by using physical and socioeconomic parameters in the Historic Peninsula. A Multi-Criteria Decision Making (MCDM) method was applied in this study because vulnerability assessments are complex and depend on many different criteria. Due to its flexible structure, the Analytical Hierarchy Process (AHP), which is one of the MCDM methods widely used in urban vulnerability assessment studies, was preferred and integrated with Geographic Information Systems. As a result of the study, it is found that approximately 49% of the district is at a moderate vulnerability level in terms of socioeconomic characteristics. For the structural characteristics, this rate is found to be at a high vulnerability level of 93%. The remaining 7% is moderately vulnerable. In this context, emphasis should be placed on identifying risky structures and strengthening and renovating them in the Historic Peninsula. The results of the method proposed in this study can be used as a basis for risk reduction studies. In addition, it can be a guide in pre-disaster risk reduction studies and can be integrated into city planning processes to keep disaster damage at minimum levels and predict the damage that may occur in settlements. The proposed method is a low-cost and short-term analysis that can be used, especially in public institutions that lack a technologically qualified workforce.

Keywords: earthquake, GIS, Historical Peninsula, Istanbul, vulnerability assessment

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1. Introduction

While the world is witnessing the most intense urbanization ever, population growth in urban areas increases the potential for disaster exposure (Dickson et al.,2012; UNISDR, 2012). It is estimated that exposure to earthquake and cyclone risk in the cities of developing countries will be more than double the current level in 2050 (World Bank and UN, 2010).

According to the report prepared globally based on the Index of Risk Management-INFORM (IASC and EC, 2020), Turkey, one of the developing countries, is in the group of "high risk" in terms of humanitarian crises and disasters with an index score of 5.0 in 2019. In terms of the hazard and exposure score of the sub-components of the index, it is the 10th most risky country (AFAD, 2020). Natural disasters cause a 3% loss in Turkey's gross national product every year, and this rate approaches 4-5% with indirect losses. On the other hand, according to the type of natural disaster, 66% of the damage was caused by earthquakes in Turkey (AFAD, 2020).

Istanbul is the leading city in Turkey and is under a severe risk of earthquake due to the North Anatolian Fault (NAF). Istanbul has become not only the financial and economic center of Turkey—Istanbul contributes the highest share of Gross Domestic Product (GDP) with 30.1% (TURKSTAT, 2021)—but also, it is one of the important historical cities hosting historically significant monumental structures in Turkey (IBB, 2018). Fatih, in particular, plays an important role in hosting the historical peninsula where the most cultural and historical heritage accumulates. However, Fatih is under the risk of disaster with a dense historical building stock that is vulnerable to earthquakes. According to the JICA (2002) report, the "heavy damage location coefficient" evaluation shows the geographical concentration of neighborhoods that require urgent action are concentrated in Fatih.

The determination of seismic vulnerability includes structural, social, economic, and physical factors. In the Historical Peninsula Management Plan (IBB, 2018), it is stated that conducted risk analyses are not sufficient for today because those analyses do not have a holistic approach. Risk analysis should consider not only all physical parameters but also social, economic, and administrative parameters as well (IBB, 2018). That is why, in this study, the Historical Peninsula is chosen as a case study area, and it is examined in the context of not only physical but also socioeconomic criteria to model seismic vulnerability. It is obvious that possible losses and damage caused by an earthquake can be reduced because of the effective implementation of risk mitigation policies. Planning decisions can be sensitive to disasters and reduce disaster losses by integrating risk and vulnerability assessment into every stage of the planning process (ISMEP, 2014a). For this reason, vulnerability information is an important input to determine the places that are likely to be damaged. Thus, this paper focuses on vulnerability assessment and aims to develop a seismic vulnerability assessment method to identify neighborhoods with high vulnerability and low coping capacity in the Historic Peninsula of Istanbul.

As the vulnerability assessments are complex and depend on many different criteria, the Multi-Criteria Decision Making (MCDM) method is applied in this study. Due to its flexible structure, the Analytical Hierarchy Process (AHP), which is one of the most widely used MCDM methods in urban vulnerability assessment studies, is preferred. Finally, a combined method of the Analytical Hierarchy Process (AHP), and Geographic Information System (GIS) is used to evaluate the seismic vulnerability.

This paper is conducted on a neighborhood basis and includes all neighborhoods of Fatih (57 neighborhoods). The criteria needed for vulnerability assessment are discussed under four main groups: structural, socio-economic, infrastructural, and critical urban facilities. It is necessary to assign weights to all earthquake vulnerability criteria and determine their degree of importance within the scope of the AHP. Experts, including a city planner, a sociologist, an architect, a civil engineer, and an environmental engineer are asked to weigh in on the criteria. Then, experts score for each main criterion and each sub-criteria by using pairwise comparison matrices.

This study, which was conducted to assess the vulnerability of physical and socio-economical parameters in earthquake-prone settlements, aimed to present an extensible earthquake-focused vulnerability assessment method suitable for integrating new data. Previous studies on earthquake vulnerability have focused more on physical parameters, while studies focusing on socioeconomic and infrastructure parameters are generally not neighborhood-based studies but cover larger areas. This study proposes a method that can be easily used by everyone by integrating all physical and social parameters with GIS.

This study can be seen as a low-cost and short-term analysis method that can be used in public institutions that have a lack of a technologically qualified workforce.

2. Theoretical Background: Hazard, Vulnerability and Risk

The vulnerability concept is one of the most significant phenomena in urban planning as it is directly related to the city's response capacity. To better understand the concept of vulnerability in urban areas, it is fundamental to have knowledge of terms like hazard, disaster, and risk. Hazard and risk are often used synonymously, but they are different concepts. All events and phenomena that have the potential to cause harm is defined as "hazard". On the other hand, "Risk" is the probability of occurrence of harm in case of hazard (ISMEP,2014b).

Cova (1999) emphasized the mathematical formula of risk defined by UNDRO as follows.

Risk = elements at risk . (hazard . vulnerability)

Wisner et al. (2004) formulated the risk as.

RISK = H x V

Where,

H indicates the probability of occurrence of natural hazards, V indicates the degree of vulnerability.

Hence, under both Wisner et al. (2004) and the UNDRO definition, it is possible to see that there is a significant relationship between risk and vulnerability at the analytical level. In this respect, it can be said that the production of risk reduction strategies basically depends on vulnerability reduction strategies. Vulnerability and risk factors in the city should be kept away from the hazard in order to lessen the chance of a disaster.

2.1. Vulnerability and Conceptual Frameworks

Although vulnerability does not have a clear definition, it is a concept used in many different disciplines and in different strands of the academic literature, such as disaster management, geography, economics, finance, sociology, environmental sciences, and engineering (Cutter,1996; Timmerman, 1981). Measurement of vulnerability has become much more complex as the vulnerability concept has advanced in recent years (Cutter et al., 2003). Cutter (1996) also supports the idea that dealing with the vulnerability is difficult, and she conducts a literature review and introduces 18 different definitions of the vulnerability. In short, vulnerability can be defined as "potential loss" (Cutter et al., 2003). According to UNISDR's terminology, vulnerability is "the conditions determined by physical, social, economic, and environmental factors or processes which increase the susceptibility of an individual, a community, assets, or systems to the impacts of hazards" (UNISDR, 2009). Understanding this concept can often be difficult due to the different dimensions it has. Rashed and Weeks (2003) explain vulnerability as "ill-structured" because there are multiple representations or understandings of vulnerability. Thus, choosing the right design structure is perhaps the most important (Rashed and Weeks, 2003) and complex process.

Birkmann (2006) underlines the complexity of the concept of vulnerability. He provides one of the best overviews of how the concept of vulnerability has broadened over time and points out that trying to establish a universal definition of vulnerability can be misleading. He explained the reason for the complexity of the vulnerability to the different definition of the concept in different field, such as disaster management and environmental studies. Therefore, the concept of vulnerability is still somewhat ambiguous (Birkmann, 2005; 2006).

There are many different approaches in the literature on vulnerability. One of the approaches is the 'Vulnerability Hazards-of-Place Model' by Cutter (Cutter, 1996; Cutter et al., 2000). This model focused on describing the place-based interaction between biophysical vulnerability and social vulnerability. In this approach, it is explained how the vulnerability of a place is determined by factors such as socioeconomic status, urbanization status, and demography. Another vulnerability framework proposed by Turner et al. (2003) focuses attention on human-environmental systems and examines the vulnerability concept more broadly (global and local level). Another model, the Earthquake Disaster Risk Index (EDRI), defines vulnerability and hazard as a component in the context of risk. The conceptual framework considers risk as the sum of four components: hazard, exposure, vulnerability, and capacity (Davidson and Shah, 1997). On the other hand, the Pressure and Release Model (PAR Model) explains risk as an intersecting combination of vulnerability and hazard, and the model is based on the widely used risk equation (Risk = Hazard x Vulnerability). PAR indicates that disasters occur when hazards affect vulnerable people (Blaikie et al., 2014).

The mentioned conceptual frameworks differ in scope. Different disciplines serve different vulnerability frameworks. There is no general model that can be applied to all fields (Birkmann, 2006). According to those models, risk is basically a function of exposure to hazard, susceptibility, and the capacity to cope with hazard (Wisner, 2016).

2.2. Indicators of Urban Vulnerability

Urban risk is defined as “in addition to natural disasters, the entire possible loss and damage that may occur due to reasons such as general layout of a city, urban texture, usage areas, existing housing, transportation systems and infrastructure, planning and management weaknesses in a city.” (ISMEP, 2014b, p.12). Because of the complexity of urban structures, urban risk and vulnerability studies also become complex and contain various indicators.

In general, urban vulnerability indicators are divided into groups as social, economic, environmental, and physical vulnerability. The main goal is to achieve a holistic approach. For example, Cardona et al. (2012) grouped vulnerability under four different main criteria. These are environmental, social, economic, and other criteria that interact and intersect. The methods for the improvement of vulnerability assessment in the European Union (MOVE) framework are discussed under six main criteria, such as physical, economic, social, cultural, environmental, and institutional (European-Union, 2015).

Structural-physical vulnerability is generally studied by engineering approaches. In general, weak points are trying to be determined by evaluating the physical factors of the city, such as buildings, roads, and infrastructure systems (ISMEP, 2014b). Mostly, studies on building characteristics and behaviors in urban systems (Karimzadeh et al., 2014) have been carried out. The reason for this is that the behavior of the building during a disaster directly determines the injury or loss of life.

Socioeconomic vulnerability has been included in many studies in the literature and Cutter is one of the most referenced. Cutter et al. (2003) broadly categorized the social vulnerability metrics such as gender, age, race and ethnicity, family structure, income, residential property, housing quality, tenancy, built environment, infrastructure, and lifelines etc.

Systemic vulnerability (also referred to as critical vulnerability in some sources) is the damage of subsystems in the urban system, rendering other systems inoperable (ISMEP, 2014b). Damages to critical urban infrastructure cause services such as hospitals and fire stations, which will be used most in the event of a disaster, to become out of use (ISMEP, 2014b). Sikich (1998) listed the infrastructure elements that could be damaged in the event of a disaster as follows: electric power supplies, gas and oil, telecommunications, banking and finance, transportation, water supply systems, emergency services. In this context, it is seen that urban vulnerability assessment indicators are very diverse and complex.

2.3. Multi-Criteria Decision Analysis

Many concepts, rules, and principles of vulnerability in cities are not precise enough. All the factors and processes that contribute to vulnerability cannot be accepted or expressed in analysis. The model should cover all aspects of possible risks while trying to avoid redundancy (Rashed and Weeks, 2003). Understanding and formulating vulnerability requires consideration of a wide variety of factors that can be addressed through an integrated approach (Cardona et al., 2012). In an integrated approach, an interdisciplinary perspective should be incorporated into risk assessment. Rosa et al. (2014) emphasized the importance of adopting a deliberative approach, using analytical methods and analysis, when assessing risks. In other words, an integrated and participatory approach is seen as one of the most appropriate methods in risk assessment studies.

Diaz-Sarachaga and Jato-Espino (2020) examined 72 urban vulnerability studies from different continents between 1998 and 2018. Among the 72 articles reviewed, Multi-Criteria Decision Making (MCDM) methods and Analytical Hierarchical Process (AHP) were the most used techniques, with 10 studies (Diaz-Sarachaga and Jato-Espino, 2020).

There are many factors that determine the seismic vulnerability of a city, and they all need to be considered at the same time. Therefore, multi-criteria decision-making (MCDM) is a suitable technique for that. It is considered one of the simplest methods to integrate all dimensions of vulnerability.

2.4. Multi-Criteria Decision Analysis and GIS

Unlike the classical MCDM process, spatial MCDM includes the spatial dimension originating from the geographical components it contains in the decision-making process. In classical MCDM studies, it is assumed that there is spatial homogeneity in decision making problems. However, as it is known, evaluation criteria can vary depending on spatial variables. Therefore, the necessity of defining new spatial dimensions for the MCDM process has emerged (Malczewski, 1999). So, Geographical Information System (GIS) integrated into vulnerability studies.

GIS-based MCDM analysis provides a useful platform for scholars, city planners or decision makers. The reason for the increase in the value of GIS in urban vulnerability analysis is that it has a technology designed to support spatial decision-making analysis and can integrate it into a field where there is a strong need to address multiple critical spatial decisions (Cova, 1999). Moreover, urban vulnerability is a spatial problem, as it is almost exclusively concerned with communities in a defined urban area (Rashed & Weeks, 2003). In general, what GIS-MCDA does is first it takes into consideration the decision-maker's concerns and use spatial data, and eventually transform spatial data into information to assist the decision-maker in choosing the best choice. Malczewski (2006) presents a very detailed literature review from 1990 to 2004. He showed that GIS-based MCDM analysis is used in many works in the fields such as environmental/ecology, transportation, urban and regional planning, waste management, water resources, agriculture and forestry, natural hazards, tourism, real estate, and geology.

2.5. AHP Method

The Analytical Hierarchy Process (AHP) is one of the multi-criteria decisions making (MCDM) methods, proposed by Saaty (1980). In this method the decision maker's problem is essentially decomposed into hierarchical sub-problems and these problems are analyzed independently. Therefore, AHP reduces the complexity of the initial MCDM problem and offers a smooth and well-structured problem. It also checks the consistency of the decision maker's evaluations to prevent biases and incorrect suboptimal decisions. AHP is based on three basic principles: dividing an existing problem into parts and comparing it by creating a hierarchy (main criteria and a set of sub-criteria in each main criteria), forming a pairwise comparison matrix for those criteria, and giving weight values by synthesizing priorities (Saaty, 1980).

AHP technique is a powerful decision support framework. Therefore, it is easy to see that there are many studies involving the AHP technique in spatial analysis. More specifically, these studies range from, seismic hazard and building vulnerability (Karimzadeh et al., 2014), land use planning (Dai et al., 2001), to residential site suitability assessment (Al-Shalabi et al., 2006).

Considering the earthquake-oriented studies in the literature; Rashed and Weeks (2003) evaluated vulnerability against earthquake hazards by using spatial MCDM with Fuzzy logic. Sarvar et al. (2011) investigated earthquake risk assessment in the Tehran Region and used a combination of TOPSIS and AHP Models. Alam and Haque (2017) studied the spatial variability of residential neighborhoods in Mymensingh using AHP. Shayannejad and Angerabi (2014) examined the earthquake vulnerability assessment of Tehran using AHP and a fuzzy logic method. Alizadeh et al. (2018) applied GIS-based MCDM to perform seismic vulnerability analysis in the residential areas of Tabriz.

3. Case Area: Earthquake Vulnerability Assessment in Historical Peninsula of Istanbul

3.1. Study Area

The city of Fatih is a peninsula surrounded by the Golden Horn, a natural harbor in the north, the Sea of Marmara and the Byzantine walls in the south, and its surface area is 15.6 km² (Fatih Kaymakamlığı, 2019). It has an urban texture consisting of organic, grid and monumental structures. Although the area has extensive commercial and tourism facilities, it is densely residential. Urban Services in Historic Peninsula have an importance throughout Istanbul. Throughout its development process from the past to the present, the Historical Peninsula has been the most densely populated area of Istanbul and has been central business area (EMBARQ, 2014).

In addition to problems such as heavy traffic flow arising from a historical city structure, there are also problems such as dense housing and population, and the inadequacy of social and technical infrastructure. Although the area has a higher daytime population, the increase is due to the number of workplaces in the region (Fatih Belediyesi, 2015). The economic activities in the area are quite intense.

The Historic Peninsula can be defined as one of the most dangerous areas in Istanbul in terms of seismicity. In the JICA (2002) report, the "heavy damage location coefficient", which shows the geographical density of the earthquake vulnerability risk, was calculated. It was seen that the neighborhoods that need an emergency action plan are concentrated in the Historic Peninsula. Istanbul's Earthquake Master Plan reports that in terms of earthquake damage, the areas requiring urgent action are mostly located in the Fatih District (IBB, 2003).

3.2. Methodology

This section explains the methodology to be used for this study and shows the main steps related to data preparation for the analysis. The research method consists of three main parts. The first part includes the determination of the criteria and data preparation; the second part contains the application of the Analytical Hierarchy Process (AHP) method in the context of expert opinions, and in the last part, spatial analysis is performed with the help of the ArcGIS program by making use of the weights obtained. The steps to be followed are shown in the process diagram in Figure 1.

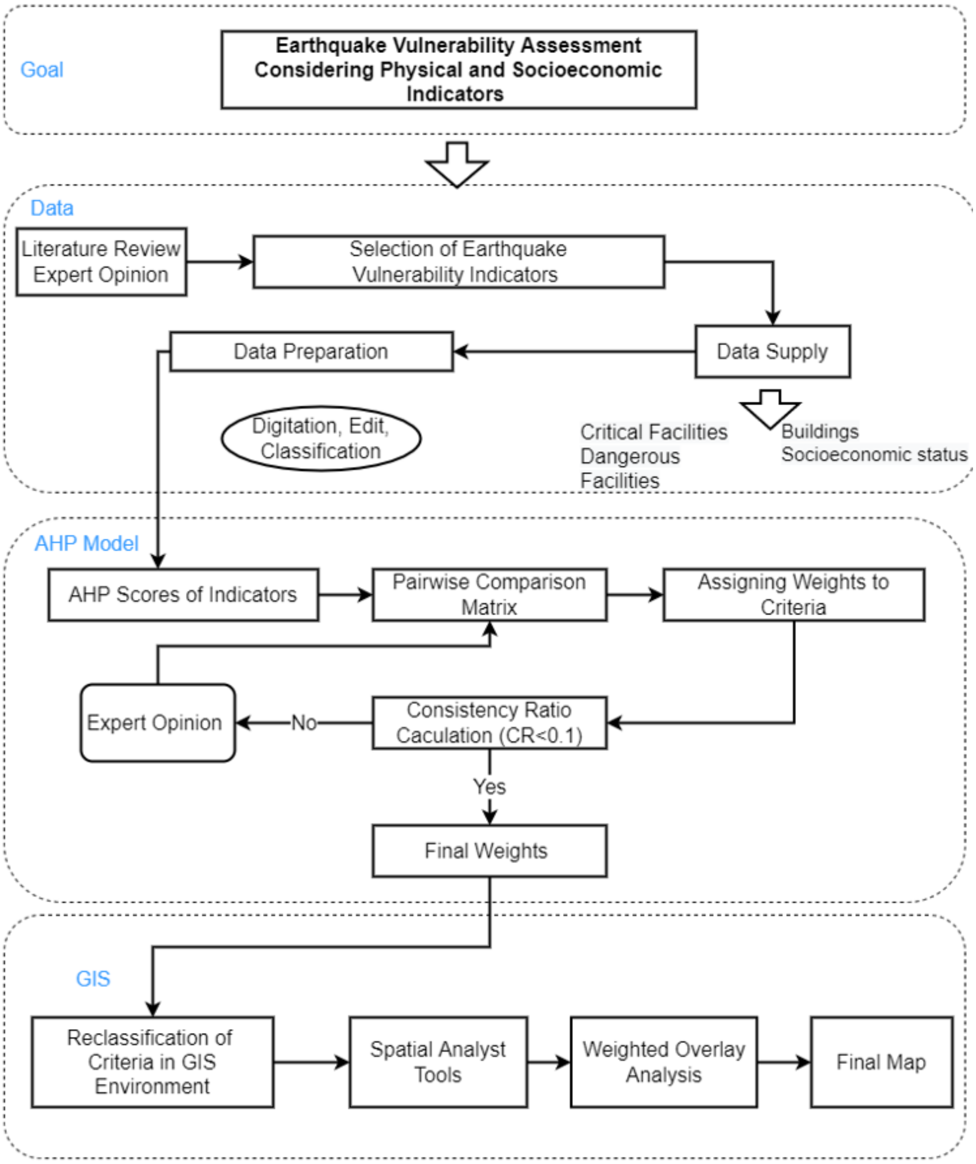

Figure 1 Process Diagram of Study.

The first stage of this study, which covers 57 neighborhoods in the Fatih district, is to determine the earthquake vulnerability criteria. The selection of criteria is determined according to the purpose of the study, theoretical frameworks, literature, and data availability. In this context, physical criteria are grouped into three main criteria. These are accessibility to critical urban services, infrastructure facilities, and structural criteria. Socio-economic criteria are grouped under a single heading. Once all the criteria are determined, the hierarchical structure is constructed (Figure 2). Unavailable data is not shown in the hierarchical structure.

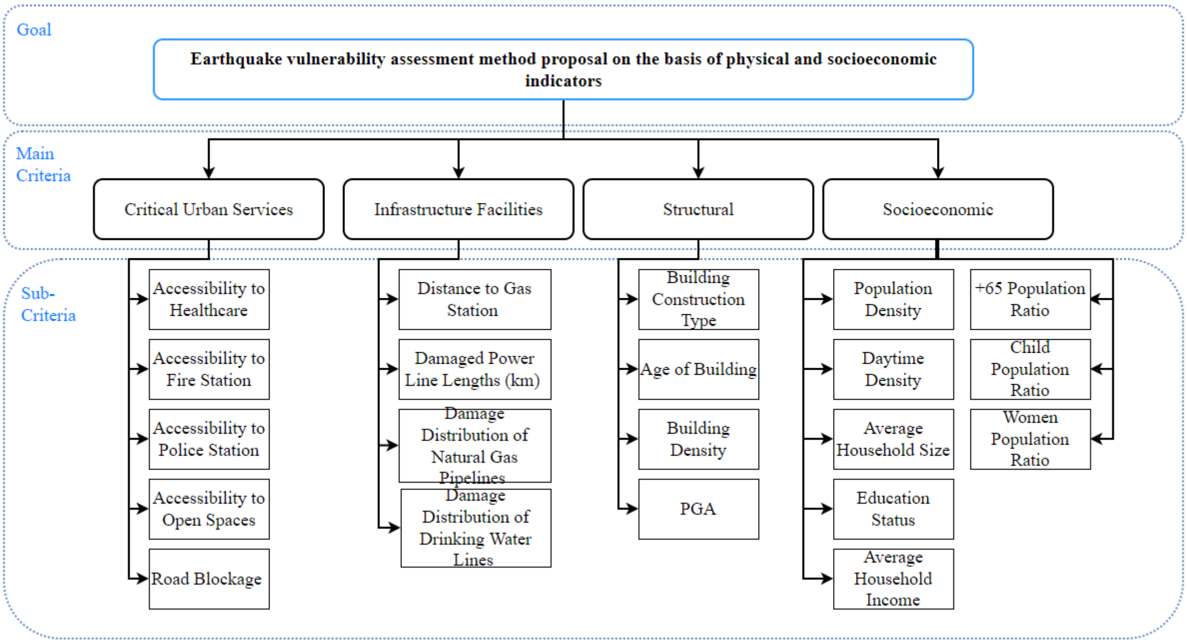

Figure 2 AHP Hierarchy of Study.

After the hierarchical structure is determined, data for each criterion is obtained in the next stage. Necessary data is requested from institutions for data supply. Some of the socio-economic data is obtained through TurkStat 2020 data and endexa.com, which publishes data based on neighborhoods by making use of TurkStat 2020 data. Infrastructure data is obtained from the JICA (2002) report. Land use, boundary and building stock data are obtained from the Istanbul Metropolitan Municipality- City Planning Department. Moreover, data such as migration, the number of disabled people, and building regulations could not be obtained. Fuel station information is downloaded from openstreetmap.org.

The data for hospitals and health centers consists of military hospitals, state hospitals, institution hospitals, private hospitals, university hospitals, foundation hospitals, SSK hospitals, clinics, family health centers, and polyclinics. Moreover, open space data consists of squares, sports fields, recreation areas, parks, green areas, and passive green areas. While determining the open spaces, the minimum size of the most suitable areas for preliminary evacuation as specified in the JICA (2002) report is taken as a basis (JICA, 2002, p.10-27). In this context, while choosing open spaces, areas with a size of 500 m2 and above are used in the analysis. Educational areas include universities as well as private schools, public schools, and foundation-owned schools. In summary, the data is separated into categories such as training areas, health areas, fire stations, and police stations.

The socio-economic data is based on neighborhoods and the analyses are carried out on the smallest administrative unit, the neighborhood. The socio-economic data consists of population density, average household size, education level, daytime density, average household income, elderly population ratio, child population ratio and woman's population ratio for each neighborhood. Daytime population is not available on a neighborhood basis. Therefore, instead of daytime population data, we use daytime density data. Daytime density data is obtained by calculating the ratio of trade and service usage to total usage (housing, etc.) on a neighborhood basis.

After the data is received from the institutions, data is made ready for analysis in the ArcGIS environment. Then the existing data are grouped according to the criteria and divided into feature classes. Polygon features are converted to point features to provide efficient use in spatial analysis. The data taken from the JICA (2002) report is converted to digitized data in the ArcGIS environment based on 500x500 m grids. After the conversion process, the data is grouped into four main criteria in the context of physical and socio-economic parameters. The sub-criteria included in these groups are divided into classes using the literature. For example, the "building construction types" criterion, which is under the structural criteria, is divided into classes such as "wood", "reinforced concrete" and "steel".

After classification, each class is scored using a 1-5 rating scale, and the highest score is assigned to the class that most affects the seismic vulnerability (Table 1).

Table 1 Classification of criteria.

Main Criteria	Sub-Criteria	Classes	Reclassification Value	Vulnerability Score	Supporting Literature
Structural Criteria	Building Age	<1980	1	5	Ghajari et al. (2017) Reveshty et al. (2014)
		1980-2000	2	3	
		>2000	3	1	
	Building Construction Type	Wood	1	2	Alizadeh et al. (2018) Alam and Haque (2018) Ghajari et al. (2017) Reveshty et al. (2014) Karimzadeh et al. (2014) Duzgun et al. (2011)
		Reinforced Concrete	2	3	
		Steel Construction	3	1	
		Masonry	4	4	
		Other	5	5	
	Building Density (building/ha)	<15	1	1	Alizadeh et al. (2018) Alam and Haque (2018) Ghajari et al. (2017) Reveshty et al. (2014) Kundak (2006)
		15-30	2	2	
		30-45	3	3	
		45-60	4	4	
		>60	5	5	
	Peak Ground Acceleration (PGA-gal)	100-200	1	1	Alizadeh et al. (2018) Rezaie and Panahi (2015) Duzgun et al. (2011) Alam and Haque (2018)
		200-300	2	2	
		300-400	3	3	
		400-500	4	4	
		500-600	5	5	
Critical Urban Services	Accessibility to Health Facilities (m)	0-500	1	1	Rezaie and Panahi(2015) Alam and Haque(2018) Shayannejad and Angerabi (2014) Merciu et al. (2018) Duzgun et al. (2011)
		500-1000	2	3	
		1000+	3	5	
	Accessibility to Fire Stations (m)	0-1000	1	1	Rezaie and Panahi (2015) Alam and Haque (2018) Shayannejad and Angerabi (2014) Duzgun et al. (2011)
		1000-2000	2	3	
		2000	3	5	
	Accessibility to Police Stations (m)	0-500	1	1	Rashed and Weeks (2003) Rezaie and Panahi (2015)
		500-1000	2	3	
		1000+	3	5	
	Accessibility to Open Spaces (m)	0-50	1	1	Servi (2004) Shayannejad and Angerabi (2014) Rezaie and Panahi (2015)
		50-100	2	2	
		100-200	3	3	
		200-500	4	4	
		500+	5	5	

Table 1 (Continuation) Classification of Criteria.

Main Criteria	Sub-Criteria	Classes	Reclassification Value	Vulnerability Score	Supporting Literature
Critical Urban Services	Road Blockage	Low	1	1	JICA (2002)
		High	2	3	
		Very High	3	5	
Infrastructure	Distance to Fuel Stations (m)	0-100	1	5	Amini Hosseini et al. (2020) Kundak (2006) Ghajari et al. (2017) Rezaie and Panahi (2015)
		100-200	2	4	
		200-300	3	3	
		300-400	4	2	
		400+	5	1	
	Damaged Electricity Line Length (km)	0-1	1	1	JICA (2002)
		1-2	2	2	
		2-3	3	3	
		3-4	4	4	
		4-5	5	5	
	Damage Distribution of Water Pipelines (Rm (PGV): damage ratio (points/km))	0-2	1	1	JICA (2002)
		2-4	2	2	
		4-6	3	3	
		6-8	4	4	
		8-10	5	5	
	Damage Distribution of Natural Gas Pipelines (Rm (PGV): damage ratio (points/km))	0-0.04	1	1	JICA (2002)
		0.04-0.08	2	2	
		0.08-0.12	3	3	
		0.12-0.16	4	4	
		0.16-0.2	5	5	
Socio-ecoomic Structure	Population Density (Person/ha)	0-100	1	1	Armaş and Gavriş (2013) Rezaei and Tahsili (2018) Kundak (2006)
		100-200	2	2	
		200-300	3	3	
		300-400	4	4	
		400+	5	5	
	Average Household Size	<2.5	1	1	Armaş and Gavriş (2013) Duzgun et al. (2011) Alam and Haque (2018)
		2.5 - 5	2	3	
		>5	3	5	
	Education Level	Illiterate	1	5	Armaş and Gavriş (2013) Cutter et al. (2003) Rezaie and Panahi (2015) Duzgun et al. (2011)
		Literate uneducated	2	4	
		Primary School	3	3	
		High School	4	2	
		Higher Education	5	1	
	Average Household Income	Hunger Limit (2651TL)	1	5	Duzgun et al. (2011)
		2651TL-8638TL	2	3	
		More than Poverty Level (8638TL)	3	1	
	Daytime Density	Very High Density	1	5	Yu and Wen (2016) Yuan et al. (2019)
		High Density	2	4	

Table 1(Continuation) Classification of Criteria.

Main Criteria	Sub-Criteria	Classes	Reclassification Value	Vulnerability Score	Supporting Literature
Socio-ecoomic Structure	Daytime Density (Trade services/total services (housing etc- neighborhood scale)	Moderate Densitiy	3	3	Yu and Wen (2016) Yuan et al. (2019)
		Low Density	4	2	
		Very Low Density	5	1	
	Elderly Population Ratio (+65)	<%5	1	1	Armaş and Gavriş (2013) Rezaie and Panahi (2015) Alam and Haque (2018)
		%5 - % 10	2	3	
		>%10	3	5	
	Child Population Ratio (<5)	<%3	1	1	Armaş and Gavriş (2013) Cutter et al. (2003) Rezaie and Panahi (2015)
		%3-%6	2	3	
		>%6	3	5	
	Woman Population Ratio	<%25	1	1	Alam and Haque (2018) Cutter et al. (2003) Armaş et al.(2017)
		%25-%50	2	3	
		>%50	3	5	

All vector data should be converted to raster data for the weighted overlay analysis. So, reclassification values are assigned to data after rating classes. The reclassification process is carried out to make the data suitable for analysis and helps to simplify and group data according to classes.

After the classes are scored, the AHP is applied. The AHP model consists of 3 different parts:

1-A hierarchy structure is constructed for main criteria and sub-criteria

2- Pairwise comparisons of the main criteria and sub-criteria are made and the weight of each is identified according to expert opinion

3- Consistency between decisions and weights is checked (Rezaie and Panahi 2015).

In this process, experts determine the order of the importance among criteria in the pairwise comparison matrices according to Saaty's (1980) score scale:

Table 2 Saaty's (1980) score (value) scale.

Score	Explanation
1	Equal Importance
3	Moderate Importance
5	Strong Importance
7	Very Strong Importance
9	Absolute Importance
2,4,6,8	Intermediate Values

The pairwise comparison matrix is constructed by taking experts' opinions. Let 'A' be a pairwise comparison matrix. If the matrix has m evaluation criteria, then the dimensions of the pairwise comparison matrix become mxm. In each entry, ajk denotes the importance level of criterion j over criterion k (jth row, kth column). Then the importance level of the criterion k over criterion j becomes akj =1/ajk. In other words, the product of the symmetric elements in matrix A is equal to ajk*akj=1. If ajk>1, it is concluded that criterion j is more important than criterion k, and if ajk<1, then criterion j is less important than criterion k. If ajk =1, it can be interpreted that both criteria j and k have equal importance. In addition, diagonal elements of the comparison matrix A become ajj=1.

After the construction of matrix A, we first derive normalized pairwise matrix of A by making the sum of each column 1, and construct the criteria weight vector by averaging the entries of each row of normalized pairwise matrix A. Then the final weight is computed by a linear sum of given weights to main criteria and sub-criteria.

We find consistency ratio (CR) as $CR = \frac{CI}{RI}$ by following Saaty (1980). CI is the consistency index and CI= $\frac{\lambda max - m}{m-1}$ where λmax is the principal (largest) eigenvalue of the pairwise comparison matrix. Similarly, RI is the random consistency index and Saaty (1980) shows the Random Consistency index as in Table 3:

Table 3 Saaty (1980) Random Consistency Index.

Random Index Values (RI)										
m	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

In conclusion, if CR <0.1 then the comparison matrix is consistent. If CR>0.1, then the pairwise comparison matrix is inconsistent. Therefore, a CR between 0 and 0.1 becomes sufficient to ensure consistency.

As a result, pairwise comparison matrixes are created according to expert opinion and Business Performance Management Singapore (BPMSG) web site used the necessary calculations of AHP (Table 4, Table 5, Table 6, Table 7, Table 8).

Table 4 Weight values of socioeconomic criteria in the context of earthquake vulnerability.

Socioeconomic Criteria	Population Density	Daytime Density	Average Household Size	Education	Average Income Rate	Elderly Population (+65)	Child Population Ratio (<5)	Women Population Ratio	Weight	Final Weight
Population Density	1	1	4	3	4	2	2	4	0.25	0.0175
Daytime Density	1	1	4	3	4	2	2	4	0.25	0.0175
Average Household Size	0.25	0.25	1	1	1	1	1	2	0.08	0.0056
Education	0.33	0.33	1	1	1	1	1	2	0.09	0.0063
Average Income Rate	0.25	0.25	1	1	1	2	2	3	0.11	0.0077
Elderly Population (+65)	0.5	0.5	1	1	0.5	1	1	3	0.09	0.0063
Child Population Ratio (<5)	0.5	0.5	1	1	0.5	1	1	3	0.09	0.0063
Women Population Ratio	0.25	0.25	0.5	0.5	0.33	0.33	0.33	1	0.04	0.0028
Consistency Ratio = % 3.1										

Table 5 Weight values of critical urban services in the context of earthquake vulnerability.

Critical Urban Services	Accessibility to Health Facilities	Accessibility to Fire Stations	Accessibility to Police Stations	Accessibility to Open Spaces	Isolation Risk Caused by Road Blockage	Weight	Final Weight
Accessibility to Health Facilities	1	1	3	4	2	0.34	0.068
Accessibility to Fire Stations	1	1	3	2	2	0.29	0.058
Accessibility to Police Stations	0.33	0.33	1	1	1	0.11	0.022
Accessibility to Open Spaces	0.25	0.5	1	1	1	0.12	0.024
Isolation Risk Caused by Road Blockage	0.5	0.5	1	1	1	0.14	0.028
Consistency Ratio = % 1.4							

Table 6 Weight values of infrastructure facilities in the context of earthquake vulnerability.

Infrastructure	Distance to Fuel Stations	Damaged Electricity Line Length (km)	Damage Distribution of Natural Gas Pipelines	Damage Distribution of Water Pipelines	Weight	Final Weight
Distance to Fuel Stations	1	3	1	6	0.42	0.084
Damaged Electricity Line Length (km)	0.33	1	1	4	0.22	0.044
Damage Distribution of Natural Gas Pipelines	1	1	1	6	0.31	0.062
Damage Distribution of Water Pipelines	0.17	0.25	0.17	1	0.05	0.01
Consistency Ratio = % 4.3						

Table 7 Weight values of structural criteria in the context of earthquake vulnerability.

Structural	Building Age	Building Construction Type	Building Density	PGA	Weight	Final Weight
Building Age	1	1	2	2	0.32	0.1696
Building Construction Type	1	1	3	3	0.4	0.212
Building Density	0.5	0.33	1	1	0.14	0.0742
Peak Ground Acceleration (PGA)	0.5	0.33	1	1	0.14	0.0742
Consistency Ratio = % 0.8						

Table 8 Weight values of the main criteria in the context of earthquake vulnerability.

Main Criteria	Structural	Critical Urban Services	Infrastructural	Socioeconomic	Weight
Structural	1	3	3	6	0.53
Critical Urban Services	0.33	1	1	3	0.2
Infrastructural	0.33	1	1	3	0.2
Socioeconomic	0.17	0.33	0.33	1	0.07
Consistency Ratio = % 0.8					

After the determination of the weights are completed, a series of spatial analyzes should be made on the data. To perform these analyzes in bulk, a basic model was created in the Geographic Information Systems (GIS) environment with the help of the model builder using ArcGIS Pro version 2.6. Part of the model (for structural criteria) is shown in the Figure 3 as an example.

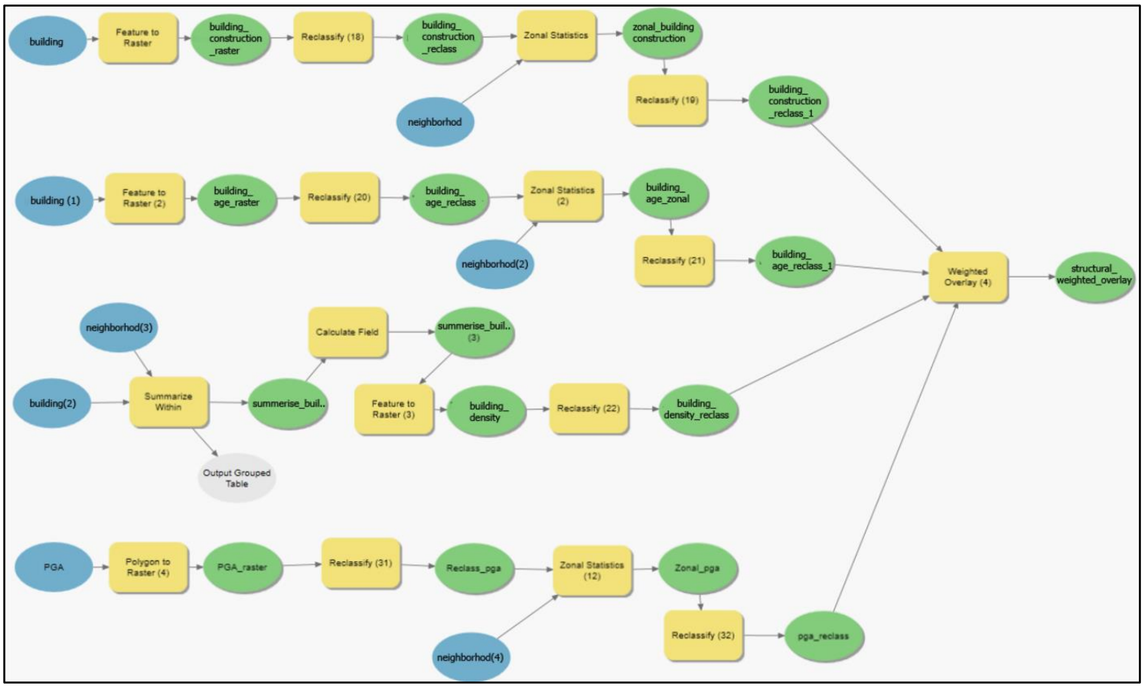

Figure 2 Model created for weighted overlay analysis of structural criteria.

Base-maps from various leading data providers, including Esri, HERE, Garmin, METI/NASA, USGS, were used via ArcGIS Pro. All data were converted into raster data as neighborhood-base according to the determined classes and values at Table 1. Subsequently, the weights obtained from the AHP process were included in the system, and weighted overlay analysis was performed based on sub-criteria first, and then all layers were combined to obtain earthquake vulnerability levels on a neighborhood basis.

4. Findings and Discussion

4.1. Structural Vulnerability Distribution

Considering the results obtained by using the opinions of the experts, it is seen that the most important criterion in terms of earthquake vulnerability is structural with a rate of 53%. Looking at the vulnerability distribution, it is seen that 50 of the 57 neighborhoods are at a high level of vulnerability in terms of structure. 93% of the study area at a high vulnerability level, and the population in these neighborhoods constitutes 99% of the total population. 1% of the population lives in areas with moderate vulnerability. The main reason why the area has such a high vulnerability potential is the risky distribution of building construction type and building age in the area. When the construction date of the buildings is examined (buildings with construction information), it is seen that 73% of them were built before 1980. Likewise, when we look at the building construction types, steel structures, which can be considered as the most earthquake resistant type, account for only 0.7% of all structures, while wooden structures have a rate of 2.5%. On the other hand, the rate of masonry structures with a higher damage potential from earthquakes is 33%.

4.2. Vulnerability Distribution of Critical Urban Services

One of the most important criteria in terms of earthquake vulnerability is accessibility to services such as hospitals and fire stations. Among the four main criteria, it is the second most important one, together with the infrastructure facilities criterion, and has a weight of 20%. In analyzing the vulnerability distribution of critical urban services across the Historical Peninsula, it is seen that only one neighborhood (Yedikule) has a high level of vulnerability. While the vulnerability level of 7 neighborhoods is very low, 42 neighborhoods are at a low vulnerability level. 4% of the population in the area is at a high vulnerability level, and 5% of the population is at a medium vulnerability level. In other words, it is thought that 9% of the total population could have problems with accessibility to urban services. The fact that the vulnerability distribution is low in general can be explained by several reasons, such as the fact that the district is home to many private and public health institutions and the fire stations are homogeneously distributed in the area. Also, the Historical Peninsula has many police stations due to its being a touristic area.

4.3. Vulnerability distribution of infrastructure facilities

According to the AHP results, like critical urban services, infrastructure facilities, they have a weight ratio of 20%. The Zeyrek neighborhood is the only neighborhood with a medium vulnerability level and its vulnerability level is higher than other neighborhoods. Zeyrek constitutes 3% of the total population. Of the 57 neighborhoods, 14 have low vulnerability and 42 have very low vulnerability levels. Only 3% of the population lives in neighborhoods that are problematic in terms of infrastructure facilities. In other words, it is seen that the vulnerability level of infrastructure systems in Fatih district during and after the earthquake is generally low.

4.4. Vulnerability distribution of socioeconomic criteria

Socioeconomic criteria are determined by experts as the criteria with the lowest weight in the context of earthquake vulnerability. The vulnerability distribution by neighborhood is shown in Figure 4.1.

26 out of 57 neighborhoods in the Historic Peninsula are at a medium level in terms of socioeconomic vulnerability. This constitutes 78% of the population. The vulnerability level of 15 neighborhoods is low. The socioeconomic vulnerability level in 16 neighborhoods could not be estimated due to the lack of information on a neighborhood basis. Since the population of these neighborhoods is less than 250 people, the data was not calculated by TurkStat on a neighborhood basis. For this reason, data based on neighborhoods could not be reached.

4.5. Overall vulnerability distribution

After creating the vulnerability maps of the main criteria separately, the weights of all sub-criteria are multiplied by the main criteria. Then the overall weight values are obtained, and a weighted overlay analysis is performed. As a result of this analysis, the general vulnerability map obtained by combining socioeconomic and physical parameters can be reached (Figure 4). As a result of the analysis, three of the 57 neighborhoods, namely Aksaray, Binbirdirek, and Süleymaniye, have a low vulnerability level. 53 neighborhoods are at moderate vulnerability levels. Those 53 neighborhoods are a bit more problematic in terms of critical urban facilities; they also have a relatively higher vulnerability in terms of socioeconomic criteria. The ratio of wooden and steel structures, which are earthquake resistant and more flexible, is only around 4% in those neighborhoods. When the buildings in the neighborhoods are examined, it is seen that 71% of the buildings were built before 1980. In light of this information, it can be concluded that detailed studies should be carried out in the context of earthquakes in 53 neighborhoods other than Aksaray, Binbirdirek, and Süleymaniye neighborhoods. The reason why the general vulnerability map gives more homogeneous results compared to the main criteria is that it is based on neighborhoods. The distribution of analyses to be made in the size of the parcel will provide more precise results. Since all parameters are combined in the general map, the general weight values are close to each other, and this leads to a more homogeneous result.

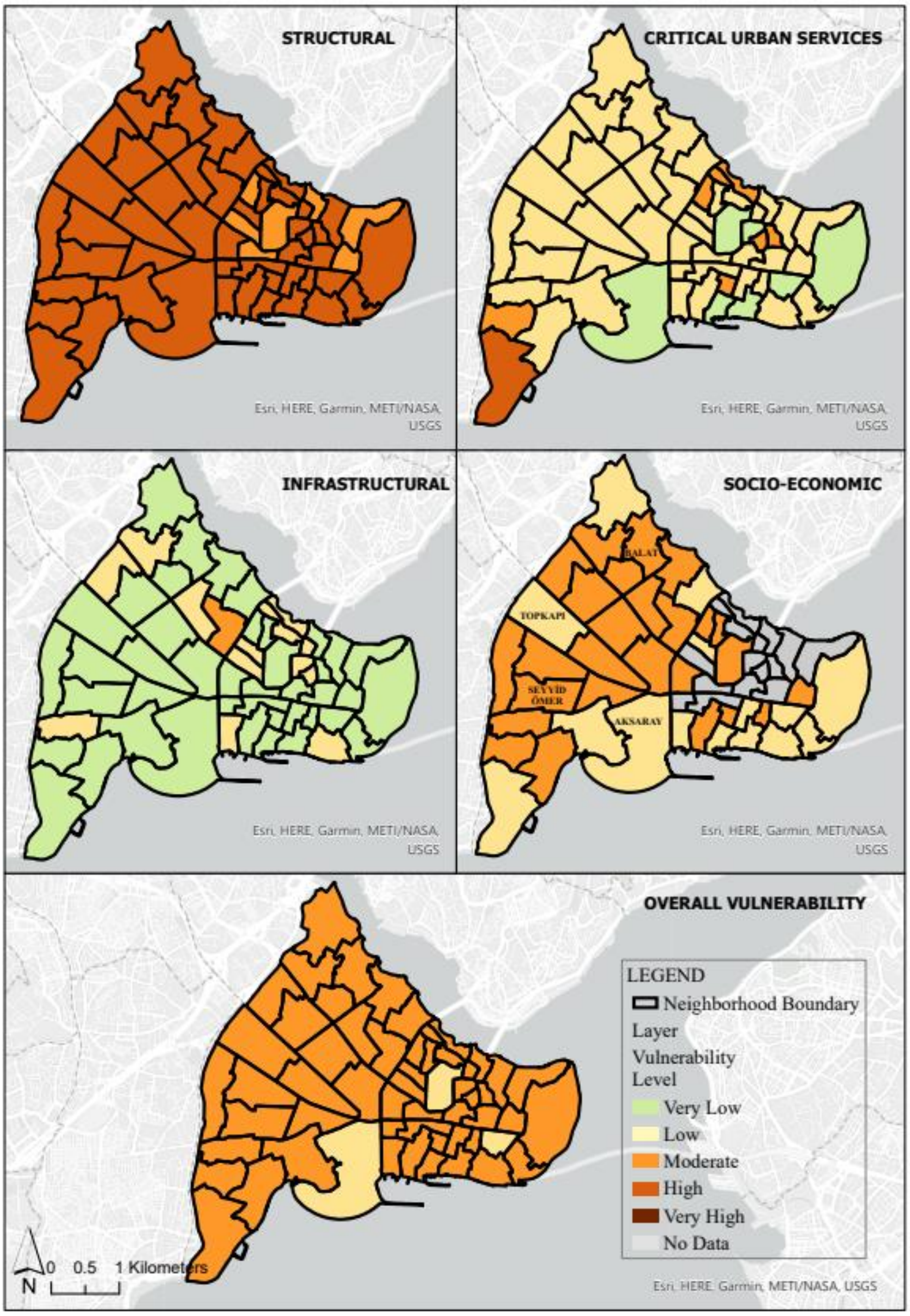

Figure 3 Vulnerability Maps of Main Criteria.

Table 9 Vulnerability Level of Neighborhoods.

Neighborhood Name	Vulnerability Level				
	Structural	Critical Services	Infrastructural	Socioeconomic	Overall
AKSARAY	High	Very Low	Very Low	Low	Low
AKŞEMSETTİN	High	Low	Very Low	Moderate	Moderate
ALEMDAR	Moderate	Low	Very Low	Moderate	Moderate
ALİ KUŞCU	High	Low	Low	Moderate	Moderate
ATİKALİ	High	Low	Very Low	Moderate	Moderate

Table 9 (Continuation) Vulnerability Level of Neighborhoods.

Neighborhood Name	Vulnerability Level				
	Structural	Critical Services	Infrastructural	Socioeconomic	Overall
AYVANSARAY	High	Low	Very Low	Low	Moderate
BALABANAĞA	Moderate	Low	Very Low	No Data	Moderate
BALAT	High	Low	Very Low	Moderate	Moderate
BEYAZIT	High	Low	Very Low	No Data	Moderate
BİNBİRDİREK	High	Very Low	Very Low	Low	Low
CANKURTARAN	High	Very Low	Very Low	Low	Moderate
CERRAHPAŞA	High	Low	Very Low	Low	Moderate
CİBALİ	High	Low	Very Low	Low	Moderate
DEMİRTAŞ	High	Low	Low	No Data	Moderate
DERVİŞ ALİ	High	Low	Low	Moderate	Moderate
EMİN SİNAN	High	Low	Very Low	Moderate	Moderate
HACI KADIN	Moderate	Moderate	Very Low	Moderate	Moderate
HASEKİ SULTAN	High	Low	Very Low	Moderate	Moderate
HIRKA-I ŞERIF	High	Low	Very Low	Moderate	Moderate
HOBYAR	High	Low	Very Low	No Data	Moderate
HOCA GIYASETTİN	High	Low	Very Low	Moderate	Moderate
HOCAPAŞA	Moderate	Low	Very Low	No Data	Moderate
İSKENDERPAŞA	High	Low	Very Low	Moderate	Moderate
KALENDERHANE	Moderate	Low	Low	No Data	Moderate
KARAGÜMRÜK	High	Low	Low	Moderate	Moderate
KATİP KASIM	High	Low	Low	Low	Moderate
KEMALPAŞA	High	Low	Very Low	Moderate	Moderate
KOCA MUSTAFAPAŞA	High	Low	Very Low	Moderate	Moderate
KÜCÜK AYASOFYA	High	Low	Low	Low	Moderate
MERCAN	High	Very Low	Low	No Data	Moderate
MESİHPAŞA	High	Low	Very Low	No Data	Moderate
MEVLANAKAPI	High	Low	Very Low	Moderate	Moderate
MİMAR HAYRETTİN	High	Low	Very Low	Low	Moderate
MİMAR KEMALETTİN	High	Low	Very Low	No Data	Moderate
MOLLA FENARİ	High	Low	Very Low	No Data	Moderate
MOLLA GÜRANİ	High	Low	Very Low	Moderate	Moderate
MOLLA HÜSREV	High	Low	Low	Low	Moderate
MUHSİNE HATUN	High	Very Low	Very Low	Low	Moderate
NİŞANCA	High	Low	Very Low	Moderate	Moderate
RÜSTEMPAŞA	Moderate	Low	Very Low	No Data	Moderate

Table 9 (Continuation) Vulnerability Level of Neighborhoods.

Neighborhood Name	Vulnerability Level				
	Structural	Critical Services	Infrastructural	Socioeconomic	Overall
SARAÇ İSHAK	High	Moderate	Very Low	Moderate	Moderate
SARIDEMİR	High	Moderate	Low	No Data	Moderate
SEYYİD ÖMER	High	Low	Very Low	Moderate	Moderate
SİLİVRİKAPI	High	Low	Low	Moderate	Moderate
SULTAN AHMET	High	Low	Very Low	Low	Moderate
SURURİ	High	Moderate	Very Low	No Data	Moderate
SÜLEYMANİYE	Moderate	Very Low	Very Low	Moderate	Low
SÜMBÜL EFENDI	High	Moderate	Very Low	Moderate	Moderate
ŞEHREMİNİ	High	Low	Very Low	Moderate	Moderate
ŞEHSUVAR BEY	High	Very Low	Very Low	Low	Moderate
TAHTAKALE	High	Low	Low	No Data	Moderate
TAYA HATUN	High	Moderate	Low	No Data	Moderate
TOPKAPI	High	Low	Very Low	Low	Moderate
YAVUZ SİNAN	High	Moderate	Low	No Data	Moderate
YAVUZ SULTAN SELİM	High	Low	Very Low	Moderate	Moderate
YEDİKULE	High	High	Very Low	Low	Moderate
ZEYREK	High	Low	Moderate	Moderate	Moderate

5. Conclusion

In this study, vulnerability assessment, which is a part of risk reduction studies, is discussed in the Fatih district in Istanbul on a neighborhood basis. A methodology is applied to determine the problematic areas by using both physical and socio-economic criteria.

Vulnerability assessments are complex in general because there are many criteria that can cause vulnerability in cities. For this reason, the analytical hierarchy process (AHP), which is one of the multi-criteria decisions making (MCDM) methods, is used in the study. Within the scope of the research, the criteria weights are calculated by taking the opinions of experts from different disciplines. Moreover, this study is integrated with geographic information systems (GIS) to make spatial evaluations.

In the terms of results, the structural criterion has the highest weight for the vulnerability assessment in the historical peninsula. 93% of the area is highly vulnerable, while the remaining 7% is moderately vulnerable. 50 neighborhoods are at a high level of vulnerability in terms of structure, and the population in these neighborhoods constitutes 99% of the total population. It can be concluded that in areas where monumental structures are concentrated, such as Eminönü and Golden Horn shores, the building stock is relatively stronger. For the other 50 neighborhoods, priority should be given to studies such as building strength tests and risky structure tests.

Considering the accessibility levels of critical urban services, there is a low level of vulnerability in general. It is concluded that 91% of the district population does not have a problem with accessing urban services.

Furthermore, considering the damage distribution of infrastructure facilities, the study shows that infrastructure is the criterion with the lowest level of vulnerability in the area. The Zeyrek neighborhood, where the historical texture is dense in terms of infrastructure facilities, is the area where the damage potential is most concentrated with its moderate vulnerability rate.

In socio-economic terms, approximately 49% of the district has a medium level of vulnerability and, 78% of the population lives in these areas. In particular, the Topkapı walls and the surroundings of Silivrikapı are problematic in socioeconomic terms.

It can be said that the areas where both socioeconomic and structural problems are clustered are generally located in the west of the district and around the city walls. Furthermore, this study reveals that Aksaray, Binbirdirek, Süleymaniye neighborhoods have lower vulnerability levels almost in all analyses made for every criterion.

When the general results obtained from the combination of the four main criteria, are examined, approximately 3% of the population lives in low vulnerable areas, and 97% of the population lives in moderately vulnerable areas.

In conclusion, this study and its spatial-based findings obtained with the proposed method can be used as a basis for the preparation of risk reduction plans and emergency management plans. Another result is that the method proposed in this study can be used as a decision support tool for city planners based on the strategic location selection approach. In addition, these methods can be used in planning processes as part of risk-reduction studies. They can also be used in the development of urban development policies.

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Resume

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