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Determination of the Earthquake Vulnerability Index for the Districts of Istanbul: An Analysis Using the CRITIC Method

İstanbul İlçeleri İçin Deprem Kırılganlık İndeksinin Belirlenmesi: CRITIC Yöntemi İle Bir Analiz

ABSTRACT

Earthquake risk is a complex phenomenon shaped not only by physical hazard characteristics but also by socioeconomic and demographic conditions. In this study, earthquake vulnerability in Istanbul districts was assessed through a data driven and objective multi criteria decision making framework. The analysis is based on a range of physical, demographic, and socioeconomic indicators, including peak ground acceleration (PGA), population structure, income level, development index (DEI), and vulnerable population groups. To ensure objectivity in the weighting process, the CRITIC (Criteria Importance Through Inter Criteria Correlation) method was used, allowing indicator weights to be determined based on their variability and the relationships between them.

The results reveal that social vulnerability indicators, particularly those related to disabled population, development level, and income capacity, play a more significant role than physical hazard intensity. The calculated vulnerability index (I_{vul}) shows significant variation among districts, indicating that earthquake vulnerability in Istanbul is highly heterogeneous and strongly influenced by local socioeconomic conditions.

This study contributes to the disaster risk literature by providing a transparent and reproducible framework for vulnerability assessment at the district level. From a practical perspective, the results offer a scientific basis for prioritizing resource allocation, supporting targeted response strategies, and developing evidence based policies in the field of disaster risk management. The proposed approach is applicable to other urban areas facing similar risks and can be further enhanced through the integration of spatial analysis and predictive modeling techniques.

Keywords: Earthquake vulnerability, Istanbul districts, vulnerability index, disaster risk, CRITIC Method

ÖZET

Deprem riski, yalnızca fiziksel tehlike özellikleriyle değil, aynı zamanda sosyoekonomik ve demografik koşullarla da şekillenen karmaşık bir olgudur. Bu çalışmada, İstanbul ilçelerindeki deprem kırılganlığı, veriye dayalı ve objektif çok kriterli bir karar verme çerçevesi aracılığıyla değerlendirilmiştir. Analiz, en yüksek yer ivmesi (PGA), nüfus yapısı, gelir düzeyi, kalkınma endeksi (DEI) ve kırılgan nüfus grupları da dahil olmak üzere bir dizi fiziksel, demografik ve sosyoekonomik göstergeye dayanmaktadır. Ağırlıklandırma sürecinde objektifliği sağlamak için gösterge ağırlıklarının değişkenliklerine ve aralarındaki ilişkilere göre belirlenmesine olanak tanıyan CRITIC (Kriterler Arası Korelasyon Yoluyla Kriter Önemi) yöntemi kullanılmıştır.

Sonuçlar, özellikle engelli nüfus, kalkınma düzeyi ve gelir kapasitesi ile ilgili sosyal kırılganlık göstergelerinin, fiziksel tehlike yoğunluğundan daha önemli bir rol oynadığını ortaya koymaktadır. Hesaplanan kırılganlık endeksi (I_{vul}), ilçeler arasında önemli farklılıklar göstermekte olup, İstanbul'daki deprem kırılganlığının oldukça heterojen olduğunu ve yerel sosyoekonomik koşullardan güçlü bir şekilde etkilendiğini göstermektedir.

Bu çalışma, ilçe düzeyinde kırılganlık değerlendirmesi için şeffaf ve tekrarlanabilir bir çerçeve sağlayarak afet riski literatürüne katkıda bulunmaktadır. Pratik açıdan bakıldığında, sonuçlar kaynak tahsisine öncelik verilmesi, hedefli müdahale stratejilerinin desteklenmesi ve afet riski yönetimi alanında kanıta dayalı politikaların geliştirilmesi için bilimsel bir temel sunmaktadır. Önerilen yaklaşım, benzer risklerle karşı karşıya olan diğer kentsel alanlara da uygulanabilir ve mekansal analiz ve tahmin modelleme tekniklerinin entegrasyonuyla daha da geliştirilebilir.

Anahtar Kelimeler: Deprem kırılganlığı, İstanbul ilçeleri, kırılganlık indeksi, afet riski, CRITIC Yöntemi

1. INTRODUCTION

Earthquakes are natural phenomena resulting from the sudden release of accumulated elastic energy within the Earth's crust, generating seismic waves that induce ground motion. In regions located along active fault lines, earthquakes represent one of the most destructive natural hazards, often leading to substantial loss of life and property (AFAD, 2023). However, contemporary research increasingly acknowledges that disaster impacts cannot be attributed solely to the magnitude of the physical hazard; rather, they are closely linked to the socioeconomic characteristics of the affected communities (Birkmann, 2006; UNDRR, 2015).

Conceptualizations of disaster risk have undergone a significant paradigm shift over time. While earlier approaches predominantly associated risk with hazard intensity, current frameworks emphasize that risk emerges from the interaction of hazard, exposure, and vulnerability components (UNDRR, 2015). Within this perspective, the severity of disaster impacts is determined not only by the magnitude of the hazard but also by the vulnerability of the exposed population (Birkmann, 2006).

In this context, social vulnerability has become a central component of disaster risk analysis. It encompasses the demographic, economic, and social characteristics that shape the capacity of individuals and communities to anticipate, cope with, resist, and recover from disaster impacts (Cutter et al., 2003; UNDRR, 2015). Key indicators including age structure, income level, educational attainment, access to healthcare services, and the presence of disadvantaged groups play a decisive role in determining the extent and distribution of disaster impacts.

A substantial body of literature has proposed index based approaches to quantify social vulnerability. Among these, the Social Vulnerability Index (SoVI), introduced by Cutter et al. (2003), is one of the most widely adopted methods for analyzing the spatial distribution of vulnerability. Similarly, Wisner et al. (2004) conceptualize vulnerability as a multidimensional construct, highlighting the critical influence of socioeconomic and demographic factors on disaster outcomes. These studies consistently demonstrate that areas characterized by higher levels of social vulnerability tend to experience disproportionately severe disaster impacts.

Empirical evidence further indicates that regions with low income levels, limited educational opportunities, and a high concentration of vulnerable populations exhibit reduced preparedness capacities and face greater challenges during post disaster recovery processes (Wisner et al., 2004). Consequently, social vulnerability assessments serve not only as analytical tools but also as essential decision support mechanisms for the formulation of effective disaster risk reduction policies.

Although these approaches have gained widespread acceptance at the global level, their implementation and scope vary significantly across national contexts. In Turkey, disaster risk assessments have traditionally focused on physical hazard analysis and damage estimation. Notably, scenario based earthquake risk assessments conducted for Istanbul provide comprehensive evaluations incorporating hazard, exposure, and building stock characteristics (Erdik et al., 2003). Nevertheless, there has been a growing recognition of the need to integrate social dimensions into vulnerability analyses. Studies in the Turkish context emphasize that earthquake vulnerability should be assessed through the combined consideration of physical attributes and socioeconomic conditions (Yücel & Arun, 2010). Furthermore, integrated assessment frameworks demonstrate that earthquake risk is inherently multidimensional, requiring the simultaneous evaluation of physical, social, and accessibility related components (Düzgün et al., 2011).

Despite these developments, a considerable portion of the literature in Turkey remains confined to analyses at the provincial scale, with limited attention to finer spatial units such as districts. This indicates that existing research falls short of providing comprehensive, integrated assessments capable of capturing spatial heterogeneity at the local level.

Turkey's location on active fault systems renders it highly susceptible to seismic hazards. This vulnerability is particularly pronounced in Istanbul, which, due to its high population density, complex urban structure, and marked socioeconomic disparities, represents one of the most at risk metropolitan areas. The impacts of a potential major earthquake in Istanbul are expected to extend far beyond physical damage, with social vulnerability playing a critical role in amplifying these effects. Moreover, significant socioeconomic and demographic disparities across districts suggest that earthquake impacts will exhibit pronounced spatial heterogeneity rather than a uniform distribution.

In this regard, the present study makes a significant contribution to the existing literature by offering an integrated earthquake vulnerability assessment for the districts of Istanbul, incorporating both social and physical indicators. By moving beyond conventional approaches that rely solely on physical damage estimation, this study provides a more comprehensive and realistic representation of disaster impacts through the inclusion of socioeconomic and demographic dimensions. The district level focus allows for a more precise identification of spatial variations in vulnerability, which is particularly crucial in metropolitan areas characterized by pronounced inequalities.

Accordingly, this study not only contributes to the academic literature but also provides a robust scientific basis for decision making processes related to disaster risk reduction, resource allocation, and the prioritization of intervention areas. In doing so, it enhances the understanding of the multidimensional nature of earthquake risk and supports the development of more resilient and sustainable urban planning strategies.

To achieve these objectives, the CRITIC (Criteria Importance Through Intercriteria Correlation) method widely used in multi criteria decision making analyses is employed to determine the weights of the selected indicators objectively, based on their variability and interrelationships (Diakoulaki et al., 1995). Within this framework, district level vulnerability indices are calculated, and spatial differences are systematically evaluated.

2. METHODOLOGY

2.1. Research Approach

In this study, a multi criteria decision making (MCDM) approach is adopted to determine the earthquake vulnerability levels of the districts of Istanbul. Since earthquake vulnerability is a multidimensional concept that requires the joint evaluation of physical hazard, demographic structure, and socioeconomic factors, it is aimed to integrate different indicators into a single composite index. In this context, the CRITIC (Criteria Importance Through Intercriteria Correlation) method, an objective weighting technique, is employed to determine the weights of the criteria. Using the obtained weights, an earthquake vulnerability index is calculated at the district level. The flowchart of the study can be found in Figure 1.

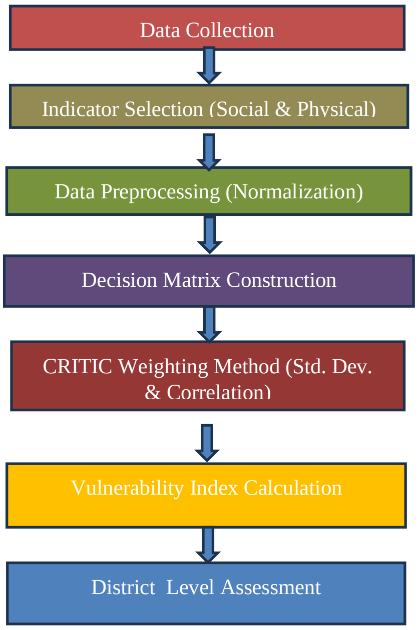

Figure 1. Methodological Framework

2.2. Data Set and Criteria

The dataset used in this study was created using data obtained from the Turkish Statistical Institute database and consists of physical, demographic, and socioeconomic indicators for the districts of Istanbul. The physical hazard component is represented by the peak ground acceleration (PGA) value, while demographic indicators include population size and the number of elderly, children, and disabled individuals. Socioeconomic indicators reflect economic well-being, transportation capacity, household structure, and the overall level of development.

The development score is a composite indicator obtained within the scope of the Socioeconomic Development Index (SEGE), developed by the Ministry of Industry and Technology of the Republic of Türkiye, and is constructed through the combined evaluation of multiple variables.

Within the scope of the index, a wide range of variables representing economic, demographic, and social structures are evaluated together. In this framework, economic variables such as employment and labor force participation rates, as well as indicators related to the industrial and service sectors, are considered alongside educational indicators including education level, literacy rates, and the number of schools and teachers. In addition, demographic variables such as the number of hospitals and hospital beds representing access to healthcare services, quality of life and infrastructure indicators, the age structure of the population, and migration movements are also among the key components of the index.

Thanks to this multidimensional structure, SEGE provides a comprehensive assessment of development that encompasses not only economic size but also social welfare and living conditions. The indicators used in this study are presented below:

Table 1. Definitions of Indicators

Category	Indicator	Year
Physical Indicator	Peak Ground Acceleration (PGA)	2024
Demographic Indicators	Total population (province level	2023
Demographic Indicators	Elderly population	2023
Demographic Indicators	Child population	2023
Demographic Indicators	Number of individuals with disabilities	2020
Socioeconomic Indicators	GDP per capita	2025
Socioeconomic Indicators	Number of motor vehicles	2023
Socioeconomic Indicators	Average household size	2023
Socioeconomic Indicators	Development score (SEGE)	2022

The physical indicator, peak ground acceleration (PGA), represents the maximum ground acceleration that occurs during an earthquake and is one of the most important determinants of physical damage. Higher PGA values increase the seismic loads imposed on structures, thereby elevating the risk of structural failure and collapse. Therefore, PGA is a fundamental indicator that directly represents earthquake hazard.

Demographic indicators, total population (province level): Population size directly determines the number of people who may be affected by an earthquake. High population density increases the risk of casualties and complicates evacuation processes during a disaster. Elderly population: Elderly individuals are considered a more vulnerable group due to limited physical mobility and the higher prevalence of health problems, which make them more susceptible to the impacts of disasters.

Child population: Children are considered a highly vulnerable group in disaster situations due to their dependency on caregivers. They have specific needs in evacuation, protection, and post disaster care processes, which increases their risk levels.

Number of individuals with disabilities: Individuals with disabilities face various constraints in preparedness, evacuation, and recovery processes. These limitations significantly increase their level of vulnerability to disasters.

Socioeconomic indicators, GDP per capita: This indicator represents the level of economic welfare and directly influences individuals' capacity for disaster preparedness and post disaster recovery. Lower income levels constitute a significant factor that increases vulnerability.

Number of motor vehicles: Considered an indicator of transportation capacity, this variable is important in terms of evacuation capability and accessibility during disasters. It also serves as an indirect indicator of economic development.

Average household size: This factor affects dependency levels and resource sharing among individuals during disasters. Larger households may be more vulnerable in terms of post disaster sheltering and resource management.

Development score: This indicator is based on the Socio Economic Development Index (SEGE), developed by the Ministry of Industry and Technology of the Republic of Türkiye, and is a composite measure derived from the integration of multiple economic, social, and demographic variables. Regions with higher levels of development tend to have stronger infrastructure, as well as better access to education and healthcare services, which enhances their resilience to disasters.

2.3. Data Preprocessing and Standardization

Since the indicators used in the study have different units of measurement, a normalization process was applied to ensure comparability. In this context, the min–max normalization method was employed.

$$x_{ij}^{*} = \frac{x_{ij} - x_j^{min}}{x_j^{max} - x_j^{min}} \quad (1)$$

As a result of the data preprocessing and evaluation stage, certain districts were excluded from the analysis to ensure the consistency and comparability of the results. In particular, the districts of Adalar, Çatalca, and Şile, along with Beşiktaş, were excluded from the scope of the study due to their relatively low population sizes compared to other districts in Istanbul and their distinct urban characteristics. Consequently, the analysis was conducted based on 35 districts.

2.4. Weighting with the CRITIC Method

The CRITIC method enables the objective determination of criteria weights by considering both the amount of information contained in each criterion and the relationships among criteria. Specifically, it is a multi criteria decision making method that evaluates the standard deviations of criteria along with the correlation relationships between them to determine the information content of each criterion and to assign objective weights accordingly (Diakoulaki et al., 1995). The effectiveness of this method has been demonstrated in various application areas in the literature (Zavadskas et al., 2014). The method is based on two main components: the standard deviation of the criteria and the inter criteria correlation.

In the first stage, the standard deviation of each criterion is calculated to determine the dispersion of the data. A higher standard deviation indicates that the corresponding criterion contains more discriminative information. In the second stage, correlation coefficients between criteria are computed to analyze information redundancy. A criterion with low correlation with other criteria is considered to contain more unique information.

Using these two components, the amount of information for each criterion is calculated as follows:

$$C_j = \sigma_j \cdot \sum_{k=1}^{n} (1 - r_{jk}) \quad (2)$$

$$w_j = \frac{C_j}{\sum_{j=1}^{n} C_j} \quad (3)$$

Through this method, variables with higher variance and lower correlation with other criteria are assigned greater weights.

2.5. Calculation of the Earthquake Vulnerability Index

Using the weights obtained through the CRITIC method, an earthquake vulnerability index was calculated for each district. In the index calculation, a weighted sum approach was employed.

$$SVI_i = \sum_{j=1}^{n} w_j \cdot x_{ij}^{*} \quad (4)$$

The obtained index values provide a comparative assessment of the earthquake vulnerability levels of the districts.

3. RESULTS AND DİSCUSSİON

This study aims to determine the earthquake vulnerability levels of Istanbul districts by constructing a composite vulnerability index within a multi criteria decision making framework. In this context, the CRITIC yöntemi was employed to objectively assign weights to physical, demographic, and socioeconomic indicators by considering both their variability and interrelationships.

Accordingly, the primary objective of the study is to evaluate and compare the relative vulnerability levels of districts based on selected indicators. The findings provide a data driven understanding of how different variables contribute to vulnerability and enable a systematic comparison of districts in terms of their relative risk level.

3.1. Interpretation of the CRITIC Based Vulnerability Index

The weighting results obtained using the CRITIC method (Figure 2.) provide critical insights into the relative importance of socioeconomic, demographic, and physical indicators in determining earthquake vulnerability across Istanbul districts.

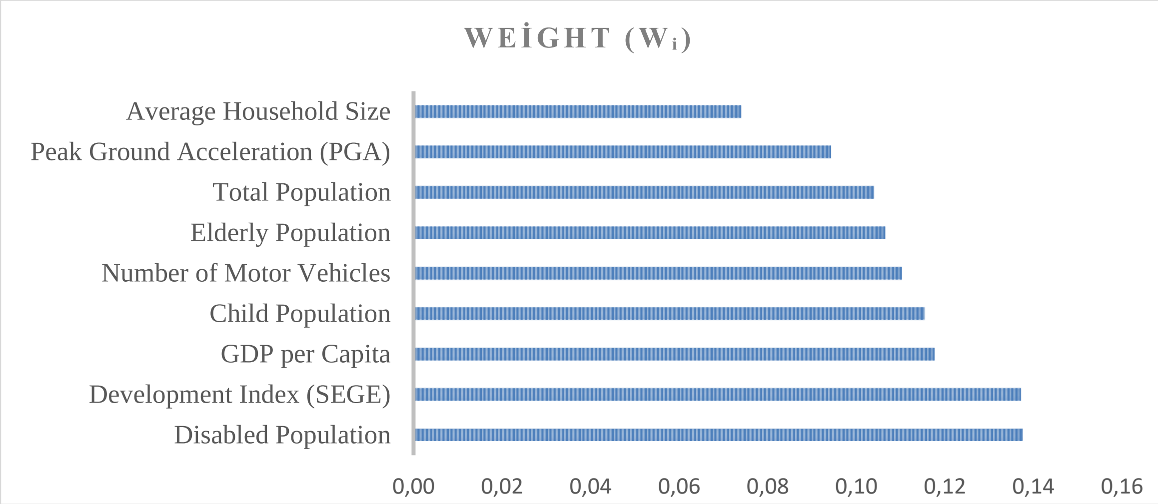

Figure 2. CRITIC Based Indicator Weights

Unlike subjective weighting approaches, the CRITIC method derives weights based on the variability and inter correlation structure of the data, thereby emphasizing indicators contain unique information.

The results indicate that disabled population (w_i = 0.1376) and development index (SEGE) (w_i = 0.1372) have the highest influence on the vulnerability index. This finding is highly consistent with the broader Social Vulnerability literature, where disadvantaged and socially dependent groups are recognized as the most sensitive segments during disaster events. According to Susan L. Cutter et al. (2003), populations with limited physical mobility and reduced access to resources tend to experience disproportionately higher impacts during natural hazards. Similarly, Joern Birkmann (2006) emphasizes that vulnerability is strongly shaped by social inequalities and adaptive capacity rather than hazard exposure alone.

The high weight assigned to the development index (SEGE) further supports the argument that socioeconomic capacity plays a decisive role in disaster resilience. Districts with higher development levels typically benefit from better infrastructure, institutional capacity, and access to services, which significantly reduce vulnerability. This aligns with the framework proposed by UNDRR (2015), which defines disaster risk as a function of hazard, exposure, and vulnerability, highlighting the critical role of socioeconomic conditions.

Following these, GDP per capita (0.1177), child population (0.1154), and number of motor vehicles (0.1103) emerge as important contributors. The influence of GDP per capita reflects the economic resilience of districts, as higher income levels enhance preparedness, response capacity, and recovery potential. The child population represents a dependent demographic group requiring additional support during disasters, which increases vulnerability, a pattern also widely acknowledged in vulnerability studies.

The relatively high weight of motor vehicle ownership can be interpreted as a proxy indicator of economic well being and accessibility. In urban disaster contexts, transportation capacity plays a crucial role in evacuation, emergency response, and access to critical services, thereby indirectly influencing vulnerability levels.

In contrast, the elderly population (0.1065) and total population (0.1040) exhibit moderate influence. While elderly individuals are typically considered a high risk group, the CRITIC method accounts for redundancy among correlated indicators, which may explain their relatively lower weight compared to other sociodemographic variables.

Interestingly, peak ground acceleration (PGA) (0.0943), representing the physical hazard component, has a comparatively lower weight. This result suggests that, within the context of Istanbul districts, variations in vulnerability are more strongly driven by socioeconomic and demographic differences than by hazard intensity alone. This finding strongly supports the argument in disaster risk literature that hazard alone is insufficient to explain disaster impacts and that vulnerability plays a central role in shaping risk outcomes.

Finally, average household size (0.0740) is identified as the least influential indicator. Although household structure may affect resource sharing and resilience capacity, its relatively low variability and correlation with other socioeconomic indicators likely reduced its discriminative power within the CRITIC framework.

Overall, the weighting results highlight that earthquake vulnerability in Istanbul is predominantly governed by social and economic fragility rather than purely physical hazard conditions, reinforcing the multidimensional nature of disaster risk.

3.2. Interpretation of the Vulnerability Index Results

The vulnerability index (I_{vul}) values calculated for Istanbul districts reveal significant differences in vulnerability levels, indicating that earthquake risk is not evenly distributed among districts and varies significantly depending on socioeconomic and demographic conditions. This finding is consistent with the disaster risk literature, which emphasizes that vulnerability is a multidimensional construct shaped by social, economic, and institutional factors (Cutter et al., 2003; Adger, 2006). The vulnerability index (I_{vul}) values calculated for Istanbul districts are presented in Figure 3.

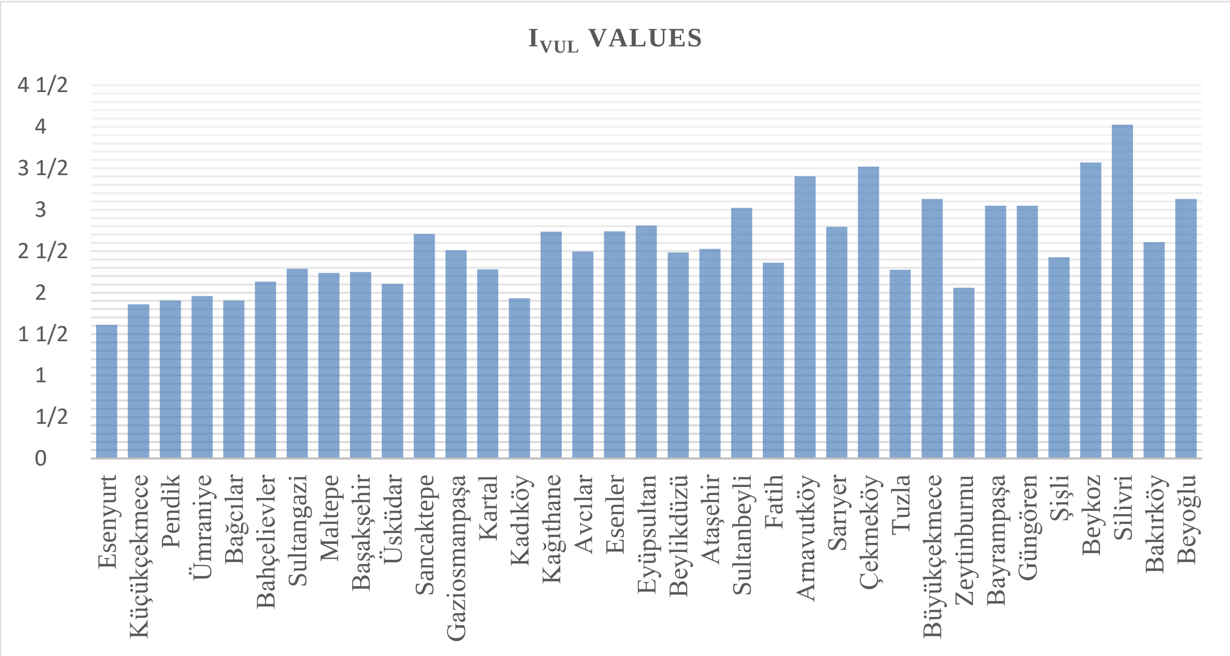

Figure 3. Earthquake Vulnerability Indices of Districts in Istanbul

The results show that Esenyurt (1.61), Küçükçekmece (1.86), Pendik (1.90), Bağcılar (1.90), and Kadıköy (1.93) have the lowest vulnerability index values, indicating relatively lower levels of vulnerability. These districts generally have stronger socioeconomic structures and better access to urban services, which increases their adaptability and resilience. As highlighted in previous studies, higher income levels and better access to infrastructure and services significantly reduce vulnerability by strengthening coping mechanisms and recovery capacity (Adger, 2006).

In contrast, Silivri (4.03), Beykoz (3.57), Çekmeköy (3.52), Arnavutköy (3.41), and Büyükçekmece (3.13) emerge as the districts with the highest levels of vulnerability. These findings demonstrate that some districts are significantly more susceptible to earthquake impacts due to limitations in socioeconomic capacity, demographic structure, or infrastructure conditions. Such differences reflect structural inequalities, which are key determinants of vulnerability in disaster contexts (Birkmann, 2006; Wisner et al., 2004).

Districts such as Sultanbeyli (3.02), Bayrampaşa (3.04), Güngören (3.05), and Beyoğlu (3.13) also show relatively high levels of vulnerability, indicating that vulnerability is not limited to a single type of urban environment but rather stems from complex interactions between demographic pressure, economic conditions, and access to services. This observation aligns with the argument that vulnerability is influenced by multiple interacting factors (Cutter et al., 2003).

On the other hand, areas with moderate vulnerability, such as Üsküdar, Bahçelievler, Maltepe, and Başakşehir, represent transitional profiles where both risk increasing and risk reducing factors coexist.

These areas may possess relatively strong infrastructure but also include sociodemographic characteristics that contribute to vulnerability, reflecting the dynamic and layered nature of urban risk (Adger, 2006).

Overall, the variability observed in I_{vul} values clearly demonstrates that earthquake vulnerability in Istanbul is highly heterogeneous and influenced by numerous interacting factors beyond exposure to physical hazard, supporting the multidimensional vulnerability framework widely discussed in the literature (Cutter et al., 2003; Birkmann, 2006).

3.3. Implications for District Level Risk Management

The findings of this study provide important insights for district level disaster risk management in Istanbul by revealing that vulnerability is primarily shaped by socioeconomic and demographic factors rather than solely by physical hazard exposure. This indicates that effective earthquake risk management strategies must move beyond hazard focused approaches and incorporate vulnerability oriented planning frameworks (Cutter et al., 2003; Adger, 2006).

At the district level, the significant variation in vulnerability index (I_{vul}) values highlights the necessity of differentiated and targeted intervention strategies. Districts with high vulnerability levels, such as Silivri, Beykoz, and Çekmeköy, require priority attention in terms of resource allocation, infrastructure strengthening, and social support mechanisms. In these districts, enhancing access to emergency services, improving transportation networks, and strengthening institutional preparedness are critical for reducing disaster impacts.

In addition, the prominence of indicators such as disabled population and development level (SEGE) suggests that socially vulnerable groups should be at the center of disaster risk reduction policies. Targeted measures such as inclusive evacuation planning, accessible shelter systems, and community based support programs are essential to ensure that disadvantaged populations are not disproportionately affected during earthquake events (Wisner et al., 2004; Birkmann, 2006).

For districts with moderate vulnerability levels, such as Üsküdar, Maltepe, and Başakşehir, risk management strategies should focus on preventing vulnerability escalation by maintaining existing infrastructure quality while addressing emerging socio demographic pressures. These districts represent critical transition zones where proactive planning can significantly enhance long term resilience.

Conversely, districts with relatively low vulnerability levels, including Esenyurt and Küçükçekmece, should not be overlooked. Maintaining and strengthening resilience in these districts is essential to sustain overall urban stability. Continuous monitoring, infrastructure maintenance, and adaptive urban planning policies are necessary to prevent future increases in vulnerability.

From a governance perspective, the results emphasize the need for data driven and evidence based decision making processes in disaster risk management. The integration of multi criteria decision making approaches, such as the CRITIC method, into planning frameworks can support local authorities in identifying priority areas and optimizing resource distribution.

In summary, the results underline that effective earthquake risk management in Istanbul requires localized, socially informed, and strategically targeted interventions, where district specific characteristics are taken into account to reduce vulnerability and enhance urban resilience.

4. CONCLUSIONS

This study provides a comprehensive and data driven assessment of earthquake vulnerability across Istanbul districts by integrating a multi criteria decision making framework based on the CRITIC method. Beyond producing a vulnerability index, the study makes a clear contribution to the disaster risk literature by demonstrating that vulnerability is predominantly shaped by socioeconomic and demographic conditions rather than solely by physical hazard exposure. In doing so, it strengthens the vulnerability centered perspective widely emphasized in disaster risk studies (Cutter et al., 2003; Adger, 2006).

A key contribution of this research lies in its ability to operationalize social vulnerability at the district level using objective weighting. While many previous studies rely on subjective or expert based weighting schemes, this study introduces a replicable and transparent approach that captures the intrinsic structure of the data. Therefore, the proposed framework can be directly applied to other metropolitan areas, contributing to comparative urban risk analysis and methodological standardization in vulnerability assessment.

From a practical perspective, the findings offer actionable insights for disaster risk management and policy making. The identification of high vulnerability districts provides a scientific basis for prioritizing resource allocation, infrastructure investments, and emergency preparedness strategies. Policymakers and local authorities can use these results to develop targeted intervention policies, particularly focusing on socially vulnerable groups such as disabled populations, children, and economically disadvantaged communities. In this context, the study serves as a decision support tool for institutions involved in disaster management, including urban planners, municipalities, and emergency response agencies.

Furthermore, the results can support the development of evidence based risk reduction policies, enabling policymakers to move beyond uniform planning approaches toward more localized and differentiated strategies. For example, district level vulnerability profiles can guide investments in resilient infrastructure, inclusive evacuation planning, and social support systems, thereby enhancing overall urban resilience.

In addition to its policy relevance, this study provides a foundation for future research and model development. The proposed vulnerability index can be integrated with hazard scenarios, damage estimation models, and machine learning approaches to predict potential losses and improve disaster preparedness planning. Moreover, combining this framework with spatial analysis techniques and geographic information systems would allow for the identification of spatial patterns and clusters of vulnerability, further enhancing its applicability.

In conclusion, this study not only advances the methodological framework for vulnerability assessment but also provides a policy relevant and practically applicable tool for disaster risk management. By highlighting the central role of social vulnerability, it offers a clear direction for both researchers and decision makers: reducing earthquake risk requires not only managing hazards but also strengthening the social and economic resilience of communities.

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