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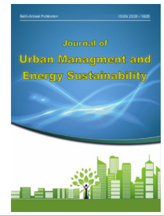

ORIGINAL RESEARCH PAPER

Evaluating Urban Vulnerabilities and Post-Earthquake Recovery Seismic Resilience of Qarchak City

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ABSTRACT

Qarchak city, undergoing rapid and often unregulated urban growth, faces significant seismic risk due to outdated infrastructure and poor compliance with contemporary seismic standards. This study aims to evaluate the city's seismic resilience by identifying its most vulnerable urban components and assessing its post-earthquake recovery potential. A combined methodology using SELENA software and GIS tools was employed to analyze seismic vulnerability based on building typologies, population density, soil conditions, and land-use zoning. Risk assessments were aligned with the Iranian Seismic Code to estimate potential casualties and economic damages. The results indicate that Region 1 of Qarchak city is the most vulnerable due to its high structural fragility and dense population. Critical weaknesses in urban planning, emergency preparedness, and regulatory enforcement were identified as key contributors to the city's heightened seismic risk. The study underscores the urgent need for urban resilience strategies, including infrastructure retrofitting, stricter enforcement of seismic codes, and enhanced community awareness. These findings offer practical insights for urban planners and policymakers. Future studies could explore dynamic modeling of post-disaster recovery scenarios and community-based risk reduction strategies.

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INTRODUCTION

Earthquakes rank among the most destructive natural disasters, inflicting significant damage on infrastructure, causing severe economic losses, and leading to considerable human casualties (USGS, 2023). Globally, these seismic events have reshaped urban landscapes, challenging communities to rebuild and adapt.Generally, seismic resilience is defined as the ability of a structure or system to continue functioning normally or to extend its serviceability after initial damage has been repaired (Motlagh et al., 2020). Countries located within major seismic belts, such as the Pacific Ring of Fire and the Alpine-Himalayan region, face heightened risks that necessitate comprehensive approaches to disaster preparedness and resilience planning (Keller and Blodgett, 2022). Historical records document numerous destructive seismic events, each leaving profound impacts on urban and rural communities. The 2003 Bam earthquake, for instance, highlighted the critical need for improved infrastructure and disaster preparedness strategies (Urlainis et al., 2023). These events underline the necessity of systematic vulnerability assessments to inform seismic hazard mitigation policies (Razavian Amrei et al., 2021). Urbanization has further compounded seismic vulnerabilities in cities. Rapid population growth, unregulated construction, and aging infrastructure contribute significantly to increased risks (An and Zhang, 2022). Vulnerability assessments have therefore become vital tools for identifying structural weaknesses and guiding the development of seismic hazard maps to inform decision-making.In recent years, studies such as Mahdavifar et al. (2023) and Liu et al. (2022) have further emphasized the role of integrated urban resilience planning, incorporating socioeconomic indicators, infrastructure robustness, and institutional capacity in seismic risk evaluation. Advancements in technology have revolutionized resilience planning. AI-driven early warning systems implemented in Istanbul provide rapid responses that significantly mitigate seismic impacts (Erdik et al., 2003). Similarly, real-time monitoring systems in Japan and California have proven instrumental in reducing risks associated with seismic activity (Plevris., 2024). These innovations emphasize the importance of incorporating cutting-edge technologies into resilience frameworks while adapting these solutions to local contexts.Nonetheless, many developing cities lack the institutional frameworks and updated databases necessary to support such high-tech systems, pointing to the need for more locally grounded and scalable approaches (Zhao et al., 2023).This study focuses on Qarchak, a city undergoing significant urbanization in Tehran Province, where seismic risks are magnified by inadequate infrastructure and unregulated construction practices. To evaluate Qarchak's seismic resilience, the study employs advanced tools such as SELENA risk analysis software and GIS platforms. These technologies have been validated globally for their accuracy in urban risk assessments (Van Westen et al., 2002). By concentrating on key parameters including building types, population densities, soil conditions, and urban zoning the research identifies critical vulnerabilities and offers insights for effective mitigation strategies.The findings highlight an urgent need for action to mitigate risks and enhance Qarchak's seismic resilience. Retrofitting aging infrastructure should be a top priority, focusing on critical facilities such as hospitals and schools (Razavian Amrei et al., 2015). Strict enforcement of construction regulations is essential to prevent unsafe structures in high-risk areas. Public awareness campaigns can equip residents with knowledge for earthquake preparedness and safe evacuation.This study demonstrates how localized assessments and targeted interventions can create safer urban environments. The findings provide a roadmap for policymakers and urban planners to prioritize actions that address structural vulnerabilities while fostering community engagement. In addition, the outcomes of this research serve as a foundation for future studies focused on dynamic simulation of post-earthquake recovery phases, risk communication strategies, and comparative analysis of resilience models across similar urban contexts.Enhancing Qarchak's seismic resilience is crucial not only for its sustainable development but also as a model for other cities in seismically active regions.

Seismic Resilience and Urban Vulnerabilities

Seismic resilience has emerged as a critical concept in the context of growing urban populations and the increasing frequency and intensity of earthquakes. Bruneau et al. (2003) introduced a foundational framework for understanding resilience, highlighting its four dimensions: robustness, redundancy, resourcefulness, and rapidity. This framework emphasizes not only the capacity to withstand seismic events but also the importance of timely and efficient recovery. More recent studies (Fang et al., 2017; Yildirim et al., 2024) have expanded this definition to consider the performance of both essential and non-essential urban systems in the aftermath of seismic disruptions.The evaluation of post-earthquake functionality has gained prominence as a practical approach to measuring resilience. Jia and Zhan (2020), for instance, proposed using functionality curves to simulate the temporal restoration of urban services, offering valuable insight into recovery planning. These models provide a quantitative basis for retrofitting decisions and highlight the variability in resilience based on local infrastructure, governance, and community preparedness.Vulnerability assessments play a complementary role by identifying the physical and systemic weaknesses that amplify seismic risks. Cimellaro et al. (2016) and Hlal et al. (2024) emphasize that resilience cannot be adequately understood without first addressing the underlying vulnerabilities of buildings, lifelines, and social systems. However, many existing assessments tend to be overly focused on physical infrastructure, often neglecting the socio-economic and institutional dimensions that shape a city's capacity to respond to and recover from disasters. Moreover, as rapid urbanization reshapes cityscapes—particularly in developing regions—the complexity of urban vulnerabilities increases. Informal settlements, inadequate enforcement of building codes, and aging infrastructure all contribute to elevated risk levels. While global research has advanced modeling tools and risk indices, their application in data-poor environments remains limited. A clear research gap exists in integrating multi-dimensional vulnerability data with dynamic resilience modeling in fast-growing cities. Bridging this gap requires context-sensitive approaches that combine quantitative tools such as GIS and simulation software with qualitative assessments of governance, social capital, and adaptive capacity. This study aims to contribute to this emerging area by applying a combined methodology in Qarchak, Iran—a city characterized by rapid growth and limited resilience infrastructure

MATERIALS AND METHODS

The research utilized version 6 of the SELENA software, an advanced tool for estimating earthquake losses developed by Molina et al. (2010). SELENA serves as a state-of-the-art decision support system for local, state, and regional officials, enabling them to estimate potential losses from future seismic events. This capability allows users to proactively anticipate the impacts of earthquakes and formulate strategies to mitigate risks. The integration of GIS-based software enhances SELENA's functionality by visually representing loss results and supporting the development of response strategies across various resolution levels (Razavian Amrei et al., 2021). In summary, SELENA is an innovative tool that empowers officials at various governmental levels to effectively estimate potential earthquake losses. Its forecasting capabilities enable proactive planning and risk reduction strategies while utilizing GIS software for visual data representation and response preparation.

Seismic Context in Iran

Situated within the Alpine-Himalayan seismic belt, Iran is one of the most seismically active regions in the world, with a long history of devastating earthquakes that have caused significant damage and loss of life (Razavian Amrei et al., 2021). Rapid urbanization, inadequate infrastructure, and widespread non-compliance with seismic building codes have further exacerbated vulnerabilities in cities such as Qarchak (Rashidinia et al., 2016). Although advanced tools for seismic risk assessment, such as SELENA and GIS, are available, their adoption in urban planning and risk management remains limited in Iran. This highlights a critical gap that requires an interdisciplinary approach, integrating these advanced tools with proactive urban planning, policy reforms, and enhanced compliance with seismic codes (Razavian Amrei et al., 2024). Such measures are essential to enhance seismic resilience and reduce the risks posed by earthquakes in urban areas.

FINDINGS AND DISCUSSION

Demographic Information and Casualty Model

The demographic structure of Qarchak plays a significant role in understanding the potential impact of earthquakes. According to the 2016 census, the total population of Qarchak was 231,075, with a relatively youthful demographic, including 71,033 individuals aged 0-14 years. This demographic data is essential for developing an accurate casualty model, which predicts the potential loss of life and economic damage in the event of an earthquake. A comprehensive casualty model integrates information about building types, population density, and the vulnerability of different demographic groups. This model serves as a vital tool for local authorities and urban planners in preparing for earthquakes, helping to assess risks based on the structural vulnerabilities of buildings and the potential impact on different segments of the population. (Table 1) and (Figure 1) illustrate the distribution of population density across Qarchak's neighborhoods. Analyzing population density provides critical insights into how different demographic groups might be affected by seismic events. (Fig. 1)

Data Collection and Preparation

To assess the seismic vulnerability of Qarchak, comprehensive geographical, structural, and demographic data were gathered from official sources and field surveys. This dataset includes details on building types, the number of floors, construction materials, soil conditions, population density, and urban zoning (Razavian Amrei et al., 2021). Additionally, historical earthquake records and seismic hazard maps were reviewed to identify risk scenarios specific to Qarchak, offering valuable insights into past seismic events and their impacts. Data for this research were sourced from the Qarchak Municipality's Urban Planning Department, ensuring accuracy and relevance. By integrating both qualitative and quantitative data, the study aims to establish a robust framework for evaluating seismic resilience and guiding urban planning and disaster preparedness strategies.

Land Use Categories and Vulnerabilities

Earthquake impacts, including loss of life and economic damage, vary significantly based on land use. This study categorizes structures in Qarchak into six major land use types (Tab. 1), each with unique vulnerabilities: Residential (RES), Commercial (COM1), Healthcare (COM6), Service (COM3), Administrative (GOV), and Educational (EDU).

•Residential (RES): Housing units are often the most affected during seismic events due to their high occupancy rates and structural weaknesses.

•Commercial (COM1): Retail and business establishments may suffer extensive damage, disrupting local economies and employment.

•Healthcare (COM6): Hospitals and medical facilities are critical during disasters; maintaining their structural integrity is essential to ensure uninterrupted care for affected individuals.

•Service (COM3): Service-oriented businesses provide essential community services, which can be severely disrupted by earthquakes.

•Administrative (GOV): Government buildings are vital for emergency response and recovery efforts, making their resilience critical for crisis governance.

•Educational (EDU): Schools and educational institutions must be designed to withstand seismic events to protect students and staff while ensuring operational continuity.

Understanding the varying degrees of vulnerability associated with each land use type is critical for effective urban planning and disaster risk reduction strategies. Prioritizing retrofitting efforts, enforcing seismic building codes, and implementing land use regulations can significantly enhance community resilience. Research demonstrates the importance of integrating seismic hazard assessments into urban development strategies. For example, studies have highlighted how strategic land use planning can mitigate earthquake risks and enhance overall urban resilience (Razavian Amrei et al., 2018).

Table 1: Types of structures in the city of Qarchak in the Hazius method

Row	Label	Description	Height			
			Average		Rang	
			Heighte	Floors	Floors	Type
1	S1L	Steel moment-frame structures, 1 to 3 floors	7.2	2	1-3	Short
2	S1M	Steel moment-frame structures, 4 to 8 floors	18	5	4-8	Medium
3	S1H	Steel moment-frame structures, more than 8 floors	46.8	13	8+	Tall
4	S2L	Steel braced-frame structures, 1 to 3 floors	7.2	2	1-3	Short
5	S2M	Steel braced-frame structures, 4 to 8 floors	18	5	4-8	Medium
6	S2H	Steel braced-frame structures, more than 8 floors	46.8	13	8+	Tall
7	S4L	Steel shear-wall structures, 1 to 3 floors	7.2	2	1-3	Short
8	S4M	Steel shear-wall structures, 4 to 8 floors	18	5	4-8	Medium
9	S4H	Steel shear-wall structures, more than 8 floors	46.8	13	8+	Tall
10	C1L	Concrete moment-frame structures, 1 to 3 floors	7.2	2	1-3	Short
11	C1M	Concrete moment-frame structures, 4 to 8 floors	18	5	4-8	Medium
12	C1H	Concrete moment-frame structures, more than 8 floors	46.8	13	8+	Tall
13	C2L	Concrete shear-wall structures, 1 to 3 floors	7.2	2	1-3	Short
14	C2M	Concrete shear-wall structures, 4 to 8 floors	18	5	4-8	Medium
15	C2H	Concrete shear-wall structures, more than 8 floors	46.8	13	8+	Tall
16	URML	Short masonry structures	4.5	1	1-2	Short
17	URMM	Medium masonry structures	10.5	3	3+	Medium

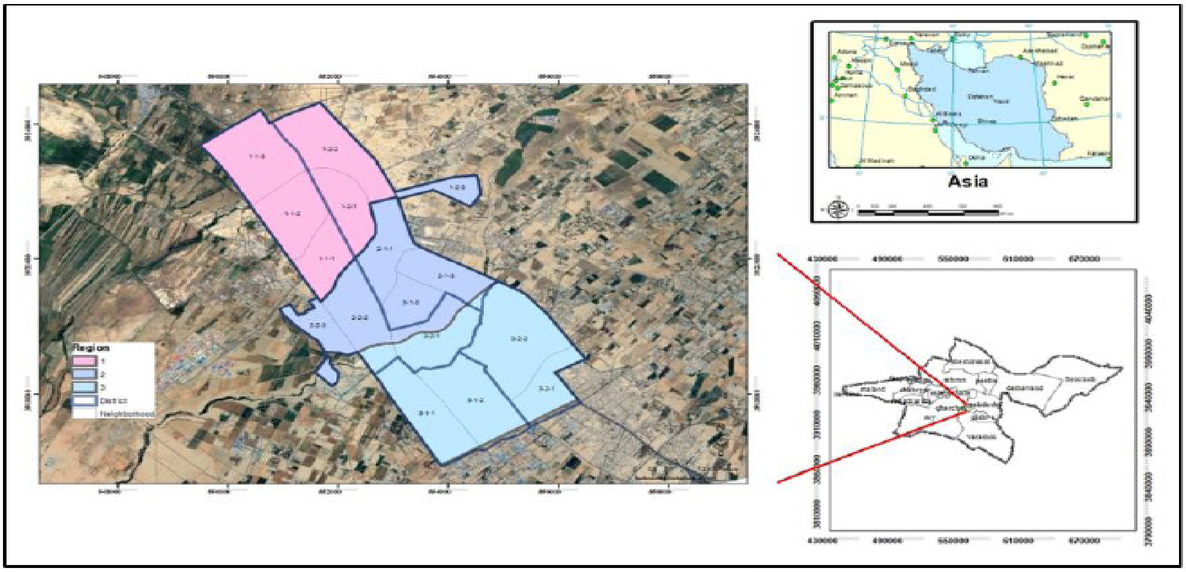

Figure 1: Qarchak city area and population density

Table 2: Building Area of Existing Structures in the Neighborhoods of Qarchak City (Square Meters)

Region Name	Neighborhood Name	Concrete	Steel	Masonry
1	1-1-1	691,592	138,474	441,571
	1-1-2	771,771	139,006	540,058
	1-1-3	123,208	821	3,289
Total Zone 1, Region 1		1,586,571	278,301	984,918
	1-2-1	757,885	98,682	484,393
	1-2-2	914,447	15,153	7,174
	1-2-3	205,879	9,601	79,827
Total Zone 2, Region 1		1,878,211	123,436	571,394
Total Region 1		3,464,782	401,737	1,556,312
2	2-1-1	781,885	216,669	275,301
	2-1-2	556,108	113,543	375,752
	2-1-3	197,588	77,723	75,353
Total Zone 1, Region 2		1,535,581	407,935	726,406
	2-2-1	456,870	110,300	130,773
	2-2-2	848,875	168,070	89,188
Total Zone 2, Region 2		1,305,745	278,370	219,961
Total Region 2		2,841,326	686,305	946,367
3	3-1-1	550,678	145,677	295,526
	3-1-2	708,095	191,608	415,381
Total Zone 1, Region 3		1,258,773	337,285	710,907
	3-2-1	284,970	52,545	95,250
	3-2-2	129,522	7,069	62,628
Total Zone 2, Region 3		414,492	59,614	157,878
Total Region 3		1,673,265	396,899	868,785

Simulation Parameters

Simulations were conducted using parameters derived from the Iranian Code of Practice for Seismic Resistant Design of Buildings, Standard No. 2800 (BHRC, 2005), which provides guidelines for earthquake-resistant design (Razavian Amrei et al., 2021). The probabilistic analysis considered multiple earthquake scenarios, ranging from moderate to severe intensity, to model potential structural damages, casualty rates, and economic losses.The assumptions, inputs, and regulations used in this research are as follows:

•Building Typology and Construction Details: The building information, including the number of floors, construction materials, and age, was categorized for input into SELENA.

•Population Density: Population distribution across different areas of the city was used to assess human exposure in various risk zones.

•Seismic Hazard Data: Earthquake scenarios were modeled based on the Iranian Seismic Code 2800, including various levels of earthquake intensity, to simulate possible structural damages, casualty rates, and economic losses.

This integration of SELENA and GIS technologies enables a comprehensive analysis of seismic vulnerability in Qarchak, facilitating targeted mitigation and risk management strategies.

Building Inventory

In the city of Qarchak, the building inventory is categorized into three primary construction types based on construction materials and methods: older masonry buildings, concrete structures, and steel-framed buildings. The masonry buildings, which are more common in older parts of the city, are considered particularly vulnerable in seismic events. Among these, masonry structures, particularly those made of mud brick, are highly susceptible to total collapse during earthquakes of magnitude 6 or greater (Ghodrati Amiri et al, 2018). This vulnerability is a critical concern for Qarchak, which still retains a significant number of these older buildings. The building inventory of Qarchak includes diverse structures that vary significantly in their seismic resilience. The distribution of building materials and construction types influences the overall vulnerability of the city to seismic events. A detailed analysis of the building areas in each neighborhood is provided in Tab. 2, giving an overview of the urban landscape and associated risks. This data is crucial for identifying areas that may require retrofitting or other interventions to improve their seismic resilience. (Tab. 2)

RESULTS AND DISCUSSION

The analysis revealed that Qarchak's rapid urbanization and population growth have significantly increased its seismic vulnerability. This observation aligns with global trends, where urban centers undergoing rapid expansion often face challenges in incorporating resilience into their planning and development frameworks (Fatemi et al., 2013). Key factors such as inadequate infrastructure, substandard building practices, and non-compliance with modern seismic codes have exacerbated the risks, particularly in densely populated neighborhoods. The integration of SELENA and GIS provided detailed insights into the city's seismic vulnerabilities (Fig. 2-8). Region 1 emerged as the most vulnerable area, characterized by:

•Densely populated zones with limited open spaces pose significant challenges for evacuation and emergency response.

•A high concentration of aging, unreinforced masonry buildings contributed to elevated damage and casualty projections.

•Casualty rates were highest in Neighborhood 2, with projected losses exceeding 15% of the population in the most severe scenarios.

•Structural damage exceeded 60% in unreinforced masonry buildings, emphasizing the need for retrofitting programs.

•Economic losses were estimated at over $50 million, primarily driven by damage to residential properties and critical infrastructure.

RESULTS AND CONCLUSION

To analyze the seismic risk for Qarchak, input data such as building characteristics, population demographics, soil types, ground motion acceleration, and other relevant parameters were carefully prepared according to the required formats of the SELENA software. The seismic risk assessment results for Qarchak City, utilizing the HAZUS method alongside the SELENA software, provided valuable insights into the damage ratios of buildings based on their types, average damage ratios segmented by urban areas, and earthquake-related casualties.It is important to note that this study did not account for the impact of non-structural components due to insufficient data availability. However, incorporating these components in future assessments is likely to yield significantly higher damage estimates.The findings underscore the critical need for enhanced seismic resilience measures in Qarchak. The assessment indicates that certain building types and urban areas are particularly vulnerable to seismic events, emphasizing the necessity for targeted retrofitting efforts and stricter enforcement of building codes. Furthermore, understanding the demographic distribution and its correlation with structural vulnerabilities can inform disaster preparedness plans and emergency response strategies. In conclusion, this research provides a comprehensive overview of the seismic risks faced by Qarchak City. By leveraging advanced analytical tools and methodologies, the study identifies key areas for intervention that could substantially enhance urban resilience against earthquakes. Moving forward, it is imperative for policymakers and urban planners to prioritize these findings in order to foster a safer and more sustainable urban environment in Qarchak and other seismically active regions.

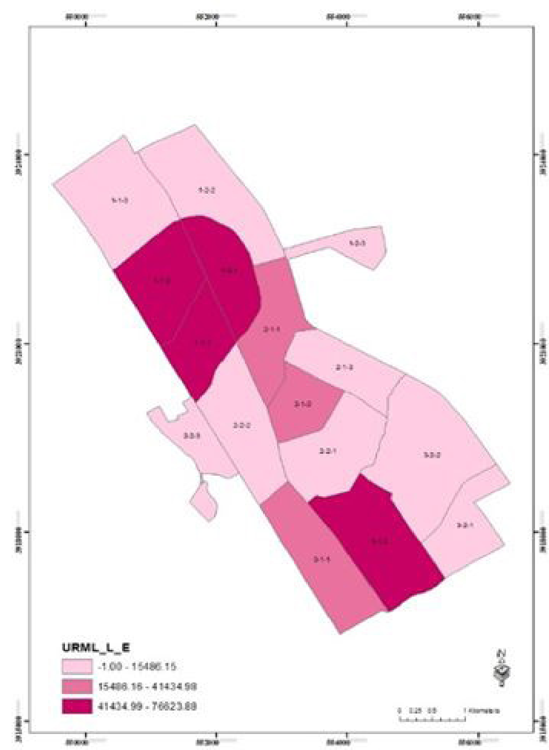

Figure 2: Extensive structural vulnerability of single-story masonry buildings

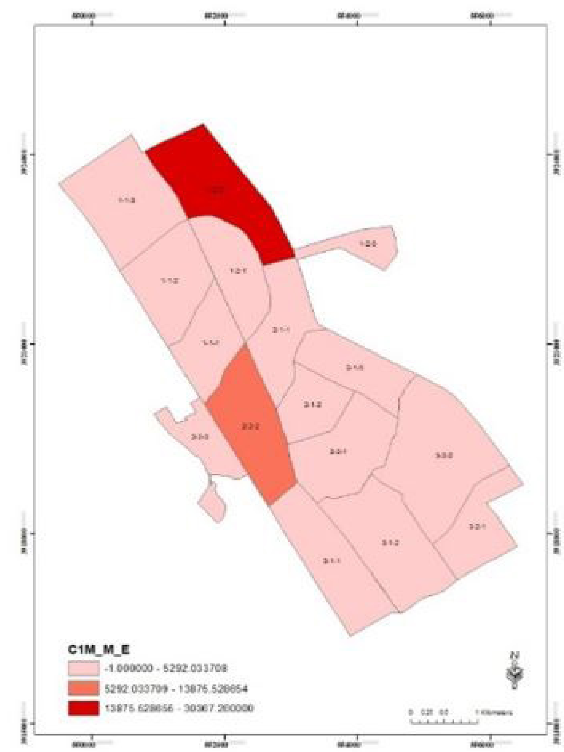

Figure 3: Extensive structural vulnerability of 4-7 story concrete buildings

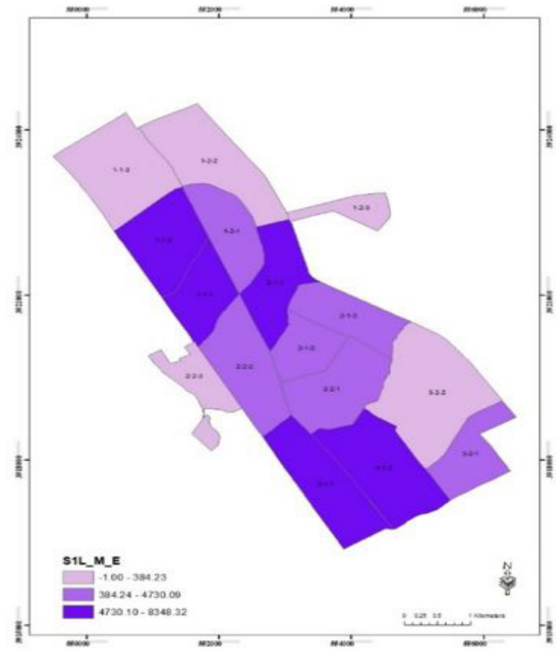

Figure 4: Extensive structural vulnerability of 1-3 story steel buildings

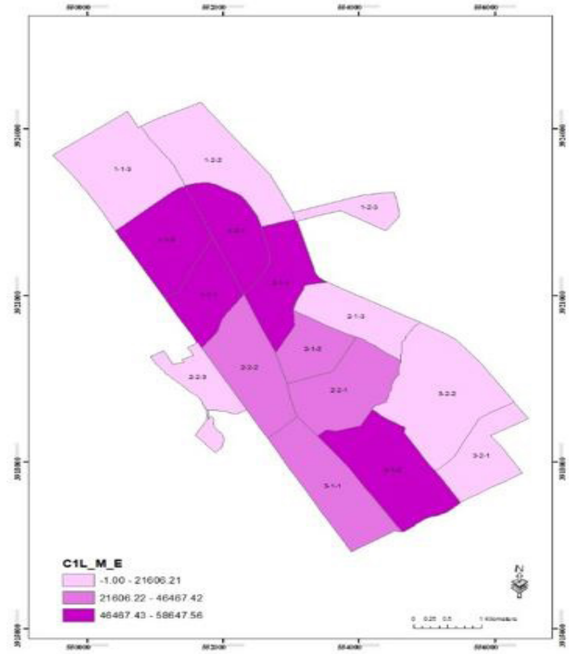

Figure 5: Extensive structural vulnerability of 1-3 story concrete buildings

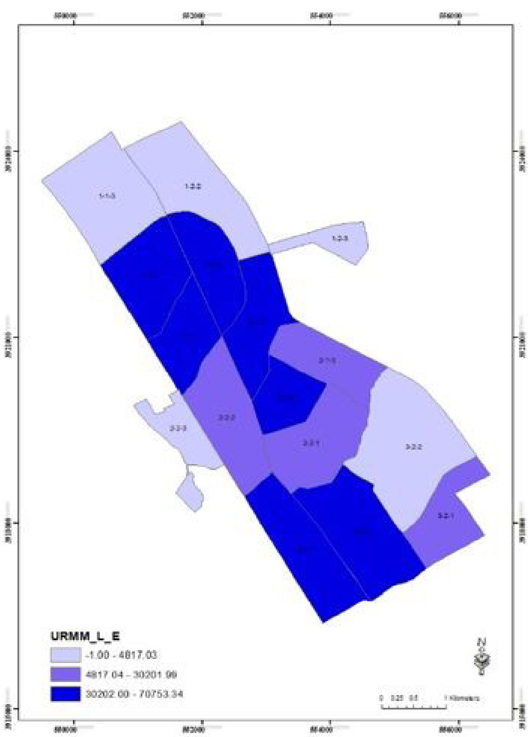

Figure 6: Extensive structural vulnerability of multi-story masonry buildings

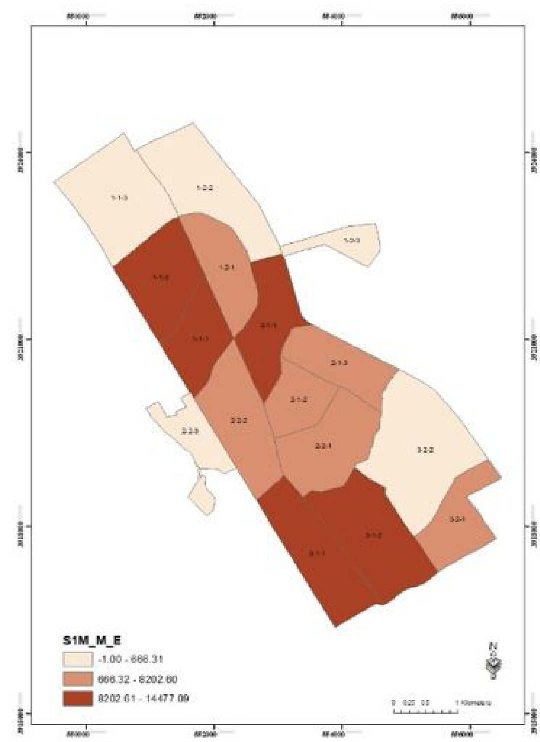

Figure 7: Extensive structural vulnerability of 4-7 story steel buildings

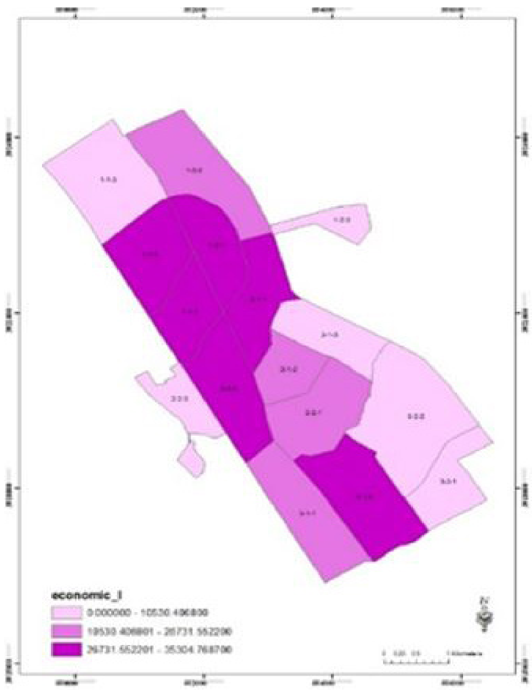

Figure 8: Estimated financial loss to the city (in Rials)

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