

Assessing Urban Flood Resilience in Megacities through an Integrated GIS–Q-Rung Orthopair Fuzzy Framework of Socio-Economic and Urban Factors

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Research Article

Keywords: Resilience, Decision-Making under Uncertainty, Floods, Urban Management, Natural Hazards

Posted Date: August 18th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10609746/v1>

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Additional Declarations:

The authors declare no competing interests.

Participant Consent: Informed consent was obtained from all experts who participated in the study. The experts voluntarily provided their opinions for the purposes of this research and consented to their participation.

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Assessing Urban Flood Resilience in Megacities through an Integrated GIS–Q-Rung Orthopair Fuzzy Framework of Socio-Economic and Urban Factors

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Abstract

Recent extreme expansion of urban sites and infrastructures has intensified flood risks in major cities, raising the ultimate call to strengthen resilience against natural hazards. Thus, this study proposes a comprehensive assessment framework to evaluate flood resilience in urban areas by integrating 12 global and 81 sub-criteria related to socio-economic and urban characteristics. A novel decision-making model under uncertainty, structured on q-rung orthopair fuzzy sets combined with GIS, was developed to capture real-world complexities in resilience analysis of urban floods. Furthermore, the implemented sensitivity analysis experiments confirmed the robustness of the model, with strong consistency observed through correlation tests. The developed approach was applied to a critical district of Tehran, Iran's capital and the largest city in Western Asia, which is a megacity highly exposed to flooding due to its location across three river basins. Using the weighted criteria, GIS-based resilience maps were generated and classified into five levels of resilience. The results indicate that 78.69% of the study area exhibits moderate or lower resilience, underscoring substantial vulnerability to future floods under shifting climate patterns. Management scenarios have been suggested to mitigate the adverse effects of the floods in urban areas that can be adapted to other flood-prone megacities worldwide.

Keywords: Resilience, Decision-Making under Uncertainty, Floods, Urban Management, Natural Hazards

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1. Introduction

Natural hazards are unexpected and sudden phenomena that weaken or destroy infrastructure, economic stability, and social well-being. Disasters caused by natural hazards such as earthquakes, floods, storms, and tornadoes may have long-term adverse effects on diverse aspects of human social life and undermine urban development and human control over environmental and urban systems. One of the critical natural hazards that should be considered in cities' environmental management is flooding. This unwanted natural phenomenon has become increasingly intense with the rapid growth of urban expansion and the development of urban infrastructure (Ward et al., 2020).

Floods have a close and complex relationship with climate, urban planning, and human activities (Adeyeye & Emmitt, 2017). In urban areas, unlike rural areas, the causes of flood risk are more convoluted, often originating from inadequate management in extensive construction development projects (Shirzadi et al., 2025).

Statistics indicate that floods are among the most significant natural disasters in terms of damage and loss (UNDRR, 2020). As urbanization continues to rise rapidly, it is crucial to learn how to coexist with floods and minimize their impacts both now and in the future. By integrating the concept of resilience into flood risk analysis and decision-making, cities can work towards becoming more resilient to natural hazards (Bertilsson et al., 2019).

As a result, preparation against such incidents requires targeted readiness. Resilience is a set of capacities that can be developed through interventions and policies, which in turn help to enhance the ability of society to respond and recover from disasters (Matsukawa et al., 2024). In making a society resilient, considering the adaptive capacities, part of the process of returning to the conditions before the occurrence of disasters affected by social, economic, institutional, and infrastructural factors to respond to the changes in risk, is tremendously crucial.

Flood resilience can significantly reduce the adverse effects and consequences of undesired climate in cities (Fu et al., 2023). Achieving resilience against flood risk depends on the existence of urban planning, an emergency response program, and developing a comprehensive plan for city resilience through the development of neighborhood resilience achievement units.

Ultimately, developing a resilient framework that can incorporate the divergent aspects of urban management, including social, cultural, and infrastructural components, requires intelligent

systems that gather information on a specific timeline and interpret it to enhance the utility of the designated scheme. Various tools have been developed to deal with such a problem. Complex network modelling has been utilized to address the flood impact on transport infrastructures in London (Bi et al., 2024). In another research, a machine learning framework was designed that assesses urban flood resilience from the resilience evolution process (Wang et al., 2024). In addition, novel metrics were introduced to assess the urban resilience against floods. The backwater effect index was introduced by Liu et al. (2025) into the global resilience analysis method to improve accuracy and evaluate the impact of green-grey-blue infrastructure on flood resilience.

It can be observed that although various tools have been utilized for urban resilience against floods, very few papers have focused on the fundamental aspects of resiliency in urban areas, in another deficiency, few researchers focused on what criteria should be investigated and what elements should be focused on or enhanced for increasing the level of resiliency against floods or natural disasters. As a result, this paper seeks to provide answers to the following questions:

- 1) What socio-economic and urban criteria, along with their related sub-criteria, influence resilience planning against floods in urban areas?
- 2) How do the identified criteria affect resilience indices?
- 3) In what ways can these criteria contribute to reducing the impacts of natural hazards, specifically floods?
- 4) What are the suitable management scenarios for mitigating the floods' consequences based on the developed model?

This paper aims to shed light on the divergent angles of defined questions by identifying the criteria affecting the defined problem and developing a novel integrated MADM-GIS model under uncertainty based on existing uncertainty in the real-world decision-making.

2. Literature Review

One of the critical issues in urban resilience is resisting various hazards such as floods. Urban resilience is related to the adaptive capacity of all urban systems, and urban flood resilience is equivalent to the adaptive capacity to deal with floods caused by climate change (Kapucu et al., 2024). Mainly in developing countries, for planning, the macro-level role and position of people to make changes is ignored, and the framework of changes is mainly from top to bottom. The lack of a complete and sufficient understanding of the target society and neglecting the importance of

social participation reduces the effectiveness of government institutions' actions in the field of crisis management and reducing damages caused by natural hazards (Haque et al., 2020). Researchers suggests that public participation plays an important role in improving correct information during floods, and strengthening public participation can be effective in prevention, preparation, response, and recovery (Cumming et al., 2015). A comprehensive literature review has been prepared in this paper to identify the research gap by analyzing case studies and implemented tools presented in Table 1.

Table 1. Literature Review

References	Tools	Indicators	Case Study
Machado et al. (2021)	Policy analysis of adaptation strategies	Green roofs, permeable surfaces, stormwater systems	General urban flood adaptation
Serre et al. (2018)	Neighborhood design resilience assessment	Transportation, land use, buildings	Neighborhoods, France
Fakhruddin et al. (2019)	Climate & hazard analysis	Climate risks	Tonga
Li et al. (2021)	High-resolution resilience index	Economic, Technical	Urban China
Feofilovs & Romagnoli (2020)	System dynamics + MCA	Multi-disaster (floods, landslides)	Latvia (medium-sized town)
Tayyab et al. (2024)	GIS + AHP + distance method	Flood resilience indicators	Peshawar, Pakistan
Zhu et al. (2021)	VIKOR + Gray Relational Analysis (GRA)	Resistance, coping, recovery, adaptation	27 cities, Yangtze River Delta, China
Pathak & Kulshrestha (2021)	Indicator-based resilience model	Physical, social, economic, demographic, infrastructural	21 districts, Narmada River, India
Zhang et al. (2021)	TOPSIS + entropy weight	Economy, society, environment, management	31 Chinese cities
Xu et al. (2021)	ISM + Network Analysis	Multi-indicator resilience	Wuhan, Nanjing, Hefei (China)
Lu & Sun (2023)	Scenario-based hydrodynamic model	Adaptive spatial strategies	Mingzhu, China

Ahmad et al. (2022)	Indicator-based resilience	Physical, social, economic, institutional, natural	3 Pakistani cities
Wu et al. (2024)	ANP + DEMATEL + GIS	Metro system flood resilience	Wuhan, China

2.1. Research Gap and Novelities

Although numerous studies with divergent techniques have focused on urban resilience assessment of cities against floods, very few available studies have investigated the diverse aspects of such a natural incident on socio-economic and urban facets in a universal model based on related criteria, with consideration of uncertainty in human decision-making. To address this gap, a novel MADM model based on the RANCOM weighting technique has been developed using q-rung orthopair fuzzy sets to assess 12 universal criteria with 81 sub-criteria, with a case study of Tehran metropolitan, capital of Iran, which is overpopulated and prone to such natural disasters, specifically floods. Furthermore, another novelty of this research lies in the risk assessment of a case study on a parcel level under uncertainty of managerial and expert levels, when the future development of an urban area is critical but underestimated. Five risk categories are identified, providing a GIS-based roadmap that enables resilience assessment and urban development planning and supports more reliable resilience assessment and structured urban development planning.

3. Methodology

The research methodology used in this study is a mixed-methods approach based on a descriptive, analytical, and exploratory case study. First, using library and articles with solid references, global experiences on urban resilience were reviewed. Next, by analyzing different models and the resilience indicators used in each model, as well as interviewing the experts, flood resilience indicators were identified. Then, using a questionnaire completed by experts, the score of each index was obtained, and the weight of each criterion was calculated using the novel q-rung orthopair fuzzy RANCOM developed in this paper. Finally, using the GIS, the developed model was implemented on the case sample. The process of applying the mentioned model is described in Figure 1.

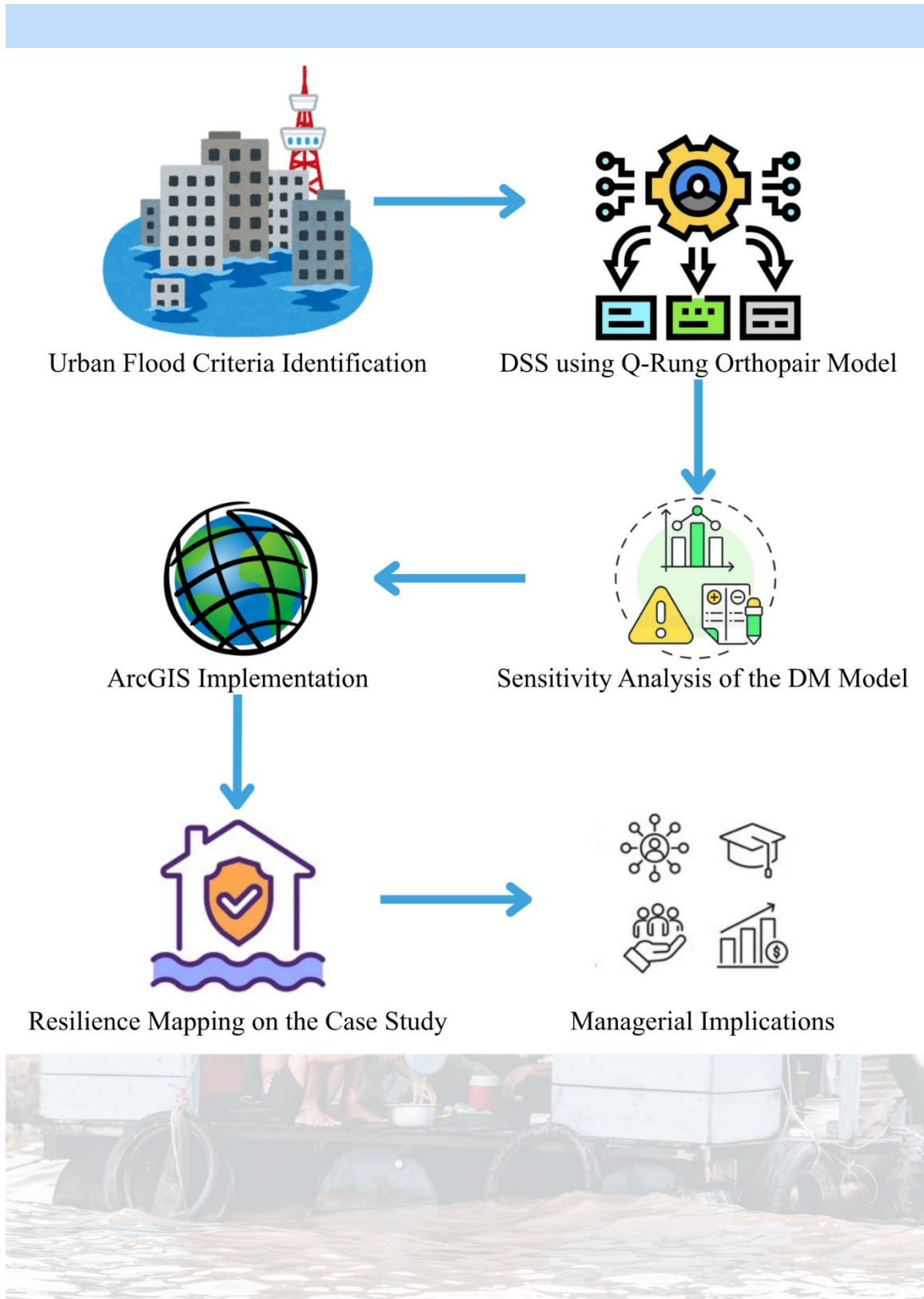


Figure 1. Research methodology stages

3.1. Q-rung orthopair fuzzy RANCOM

The Q-rung orthopair Fuzzy RANCOM method is a novel decision-making framework designed in this research to prioritize or rank interrelated criteria in complex systems. It is particularly useful in fields like disaster resilience, urban planning, infrastructure evaluation, or organizational assessment, where interdependencies and uncertainty in judgments are prevalent. It builds upon the classical RANCOM (Ranking of Interrelated Criteria by Mutual Comparison) method by integrating Q-Rung Orthopair Fuzzy Numbers (QROFNs) to handle uncertainty and hesitation in expert linguistic judgments more flexibly than standard fuzzy or intuitionistic fuzzy approaches. Q-rung orthopair fuzzy numbers exhibit superior capability in handling judgment uncertainty and provide a higher representation capacity compared to other fuzzy models (Peng and Luo, 2021). RANCOM is based on pairwise comparisons of criteria, where each criterion is compared against the others using linguistic scales. The degree of influence of one criterion over another is evaluated in a matrix, and the row-wise sum of influence scores indicates the overall importance of each criterion (Więckowski et al., 2025).

3.1.1. Q-Rung Orthopair Fuzzy Numbers (QROFNs)

A QROFN is defined by a pair (μ, ν) where (Ecer et al., 2023):

μ is the degree of membership,

ν is the degree of non-membership,

And for a given $q \geq 1$, it must hold that:

$$\mu^q + \nu^q \leq 1 \quad (1)$$

This form provides greater flexibility than Intuitionistic or Pythagorean fuzzy numbers, especially when experts are uncertain or hesitant in their judgments.

3.1.2. Score function for QROFN

To rank or evaluate criteria, we use a score function:

$$S = \mu^q - \nu^q \quad (2)$$

This captures the net support for each criterion considering both positive and negative information.

3.1.3. Procedure of Q-Rung fuzzy RANCOM

Step 1. Input the pairwise linguistic matrix

Experts compare each criterion with others using linguistic terms (Very Low, Low, Equal, High, Very High). A square matrix is formed where each cell represents the influence of one criterion over another.

Step 2. Convert linguistic terms to QROFNs

Table 2 is used for conversion of linguistic terms to QRFONs:

Table 2. Linguistic terms and their numerical equivalents

Linguistic Term	(μ, ν)
Very Low (VL)	(0.45, 0.15)
Low (L)	(0.55, 0.25)
Equal (E)	(0.50, 0.50)
High (H)	(0.75, 0.45)
Very High (VH)	(0.95, 0.55)

Step 3. Calculate sums for each criterion

For each criterion, a row-wise addition according to the following equations is considered:

$$\mu_{sum} = \left(\sum_i \mu_i^q \right)^{\frac{1}{q}} \quad (3)$$

$$\nu_{sum} = \left(\sum_i \nu_i^q \right)^{\frac{1}{q}} \quad (4)$$

Step 4. Obtain the q-rung score function

The score function will be obtained using the following formula based on the previous steps:

$$S = \mu_{sum} - \nu_{sum} \quad (5)$$

Step 5. Calculate the final weights

The final weights will be calculated using the values from step 4 based on the following equation:

$$w_i = \frac{S_i}{\sum S_i} \quad (6)$$

4. Data gathering

At the first step, professionals with experience in crisis management and urban planning convened at an online conference to discuss the gathered criteria. Experts include four civil engineers, five specialists in urban design, five managers in Crisis Management, and three top urban managers.

4.1. Urban resilience

Resilience theory was first used in the 1960s to 1970s as a new ecology (Petrescu & Baibarac, 2017). The idea of resilience is the ability of an institution or system to reschedule and respond to disruption or cessation in some cases (Martin et al., 2016). Campanella (2006) defines urban resilience as a city's ability to recover from destruction. Given the unprecedented environmental, social, and economic challenges of the 21st century, it is essential to seek solutions that enhance the resilience of cities and their residents (Baibarac and Petrescu, 2017).

Currently, many cities face vulnerability due to natural and man-made crises, which result in physical, economic, social, and cultural losses. Therefore, it is crucial to redefine urban development with a focus on urban resilience in this century. Applying the resilience concept to urban systems is an innovative approach that highlights the capacity of cities as complex systems composed of diverse components. As a result, a roadmap for resiliency improvement is needed to reassure sustainable planning against natural hazards like floods.

4.2. Resilience assessment criteria

There is a consensus about the factors that create vulnerabilities and those that improve and promote the resilience of society, but there is less consensus on the measurement. Therefore, the strength of societies cannot be measured directly, and there is a critical need to create resilience indicators. According to the conducted literature review, the main dimensions that affect vulnerability and resilience are physical, social, political, economic, organizational, and ecological components. Table 3 lists some of the most important studies that have been conducted in the field of disaster resilience, with a focus on floods.

Table 3. Research criteria and sub-criteria

Dimension	Criteria	Sub-criteria	Measure	Reference
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Physical Dimension	Land use	Floodplain buffer	Distance to rivers	Bahrami et al. (2019)
		Land use adjacency	Compatibility and incompatibility of land uses	Bukvic et al. (2021)
		Site selection	Proximity to water bodies	Abisoye et al. (2023)
		Land use mix and functional diversity	Land use diversity	Dornkamp et al. (2025)
		Safety buffer zones of hazardous facilities (explosive, flammable facilities and with the ability to release toxic substances)	Distance to petrol and CNG pumps Oil and gas network	Bitarafan et al. (2025)
		Buffer zones of industries and infrastructures	Distance to factories and mines, Distance to water and sewage infrastructure, Distance to power infrastructure, Distance to telecommunications infrastructure	Pearson et al. (2018), Fekete (2019), Deshmukh et al. (2011) Bitarafan et al. (2025)
		Dependence and interaction of infrastructures	Infrastructure sensitivity matrix	Fekete (2019)
		Water availability	Access to water supply network	Tarani et al. (2019)
		Power availability	Access to power network	Souto et al. (2022)
		Gas availability	Access to gas network	Dell'Isola et al. (2020)
Urban spatial structure		Availability of cyber infrastructures	Smart city indicators	Panda and Bower (2020)
		Urban texture and pattern	Identifying regular segmentation pattern, square or rectangular,	Esposito and Pinto (2014)

		polygonal square (obtuse and acute angles)	
	Urban form	Identification of linear, wide, galactic, concentrated, star (radial) and ring forms	Bertilsson et al. (2019)
	Urban readability	accessibility light and color Existence of symbols and key buildings	Bertilsson et al. (2019)
Structure	Unauthorized constructions	Percentage of unauthorized constructions	Simpeh et al. (2023)
	Site coverage	Site coverage percentage	Rose et al. (2016)
	Building age	Percentage of buildings under 30 years to total buildings	Proversbs and lamond (2017)
	Materials	Material of the structure	Proversbs and lamond (2017)
	Structure	Type of structure (quality)	Bertilsson et al. (2019)
	Building density	Building density percentage	Wijayawardana et al. (2023)
	Compliance with building codes	Percentage of compliance with construction regulations such as earthquakes	Ahmed et al. (2018)
	Number of floors	Building height	Adedeji et al. (2024)
Architecture of buildings	Building openings	Number of openings	Mannucci et al. (2022)
	Characteristics of the entrance to the building	Number of entrances	
	Decoration of buildings	Percentage of decorations	Aerts et al. (2011)
	Interior spaces of the building	Availability of flood-resistant interior design features	Bitarafan et al. (2016)
			Nakhaei et al. (2016)

Social and Cultural	Natural factors	Independence of building spaces	Independence percentage	
		Vegetation cover	Percentage of land surface covered by vegetation	Shilpakar et al. (2021)
		Runoff depth	Depth of water from precipitation that becomes surface runoff	Zhang et al. (2023)
		Basin shape	Ratio describing basin geometry	Wu et al. (2020)
		Water infiltration rate	Rate at which soil absorbs water	Zhang et al. (2023)
		Basin area and Runoff volume	Total surface area draining into a given outlet	Wu et al. (2020)
		Flood return period	Average recurrence interval for a certain flood magnitude	Zhang et al. (2023)
		Soil texture	Soil type	Patel et al. (2021)
		Ground material	Rock type	Robinson (2012)
		Lithology	Dominant rock or soil type affecting permeability and erosion potential	Estelaji (2023)
	Transportation network	Access to roads	Percentage of access to roads	Xu et al. (2024)
		Width of roads	Percentage of width of roads	Beevers et al. (2012)
		Road hierarchy	First, second, third and local centers	Beevers et al. (2012)
		Level of enclosure	ratio of road width to wall height	Xu et al. (2024)
		Bridge buffer zone	Distance to bridges	Beaver and Mitoulis (2024)
	Population	Population density and distribution	Population density and spatial distribution	Arosio et al. (2021)
		Population growth	Population growth rate	Hemmati et al. (2020)
		Native population	Percentage of native population	Hemmati et al. (2020)

Economic	Social capital		to the total population	
		Household size	Average number of people in a family	Hemmati et al. (2020)
		Population age	Age structure of the population	Soetanto et al. (2017)
		Population literacy	Ratio of the educated population to the total population	McEwen et al. (2017)
		Gender ratio	Ratio of the number of men to women	Gaisie et al. (2022)
		People in need of support (elderly, children, disabled, etc.)	People in need of support (elderly, children, disabled, etc.)	McEwen et al. (2017)
		Hazard awareness	Awareness level	O'Sullivan et al. (2012)
		Training in safety regulations against threats	Number of training hours	Karrasch et al. (2021)
		Sense of belonging and satisfaction	Satisfaction percentage	Quinn et al. (2020)
		Social cohesion during crises	Social cohesion	Ntontis et al. (2020)
		Social anomalies	Percentage of social crimes during crisis	Haque et al. (2022)
	Income and Employment	Insurance coverage	Ratio of medical insurance to society ratio of accident insured to society	Rumson and Hallett (2019)
		Income per capita	Ratio of people above the poverty line to society	Cao et al. (2023)
		Access to banking facilities related to risk reduction and crisis management programs	Percentage of satisfaction	Hussain et al. (2021)
		Housing price	Average housing price	Wang (2019)
		GDP per capita	GDP per capita	Cao et al. (2023)

		Employment rate	Distribution and structure of employees according to major activity groups	Cao et al. (2023)
		Nature of the household head's occupation	Job category	Srivastava and Shaw (2015)
		Labor force size	Ratio of the population aged 15 to 64 to the total population	Hemmati et al. (2020)
Safety and Security	Access to emergency response facilities	Hospitals and relief centers	Access to hospitals and relief centers	Rattanakanlaya et al. (2022)
		fire stations	Access to fire stations	Fekete et al. (2017)
		Green and open spaces	Access to green and open spaces	Schuch et al. (2017)
		Temporary shelter centers	Access to Temporary shelter centers	Melgarejo and Lakes (2014) Nakhaei et al. (2015)
		Emergency telecommunication network	Access to emergency telecommunication network	Marshall et al. (2023)
		Emergency evacuation routes	Access to Emergency evacuation routes	Musolino et al. (2022)
		Multipurpose spaces	Access to religious use Sports use Educational use Therapeutic use	Denipitiya and Udalamaththa (2018)
		Police centers	Access to police centers	Singh et al. (2021)
Organizational	Institutional platform	Existence of institutions related to crisis management	percentage of relationships with crisis management organizations	Singh et al. (2021)
		Presence of community organizations	number of community organizations	Perera et al. (2020)

Institutional performance	Level of public participation in decision-making for crisis management	Percent of eligible population involved	Mees et al. (2017)
	Presence of crisis management programs and codes	Number of programs and codes in the field of crisis management	Singh et al. (2021)
	Extent of citizen participation with local governance bodies	Citizen participation percentage	Mees et al. (2017)
	Preparedness programs (exercises, drills, and simulations)	Existence and number of Preparedness programs	Singh et al. (2021)
	Capacities and capabilities of institutions	percentage of relationships between institutions	Ro and Garfin (2023)
	Having a risk mitigation plan	Percentage of effectiveness based on simulations	Waghwal and Agnihotri (2019)
	Rapid alert system related to hazards	Existence of the system	Perera et al. (2020)
	Presence of emergency command and damage evaluation systems	Existence of the system	Kim et al. (2017)
	Presence of rapid response teams	Percentage of effectiveness of rapid response teams	McEwen et al. (2018)

5. Results

Using the novel q-rung orthopair fuzzy RANCOM introduced in this paper, 12 main criteria based on 81 sub-criteria were analyzed to understand their importance while developing resiliency maps. Five universal dimensions were considered to assess the resilience criteria of cities against floods.

According to the model's results based on the experts' opinions, the physical dimension scored the highest, which can be attributed to the direct and strong relationship between this dimension and the level of vulnerability and human casualties. It can be concluded that land use, natural factors, and the structure of the buildings were the top three crucial criteria in developing roadmaps for urban resilience against floods. Figure 2 illustrates the final criteria weights, calculated using the novel MADM model employed in this research, and implemented in Python coding language within the Google Colab environment. The calculation steps are described in Appendix A.

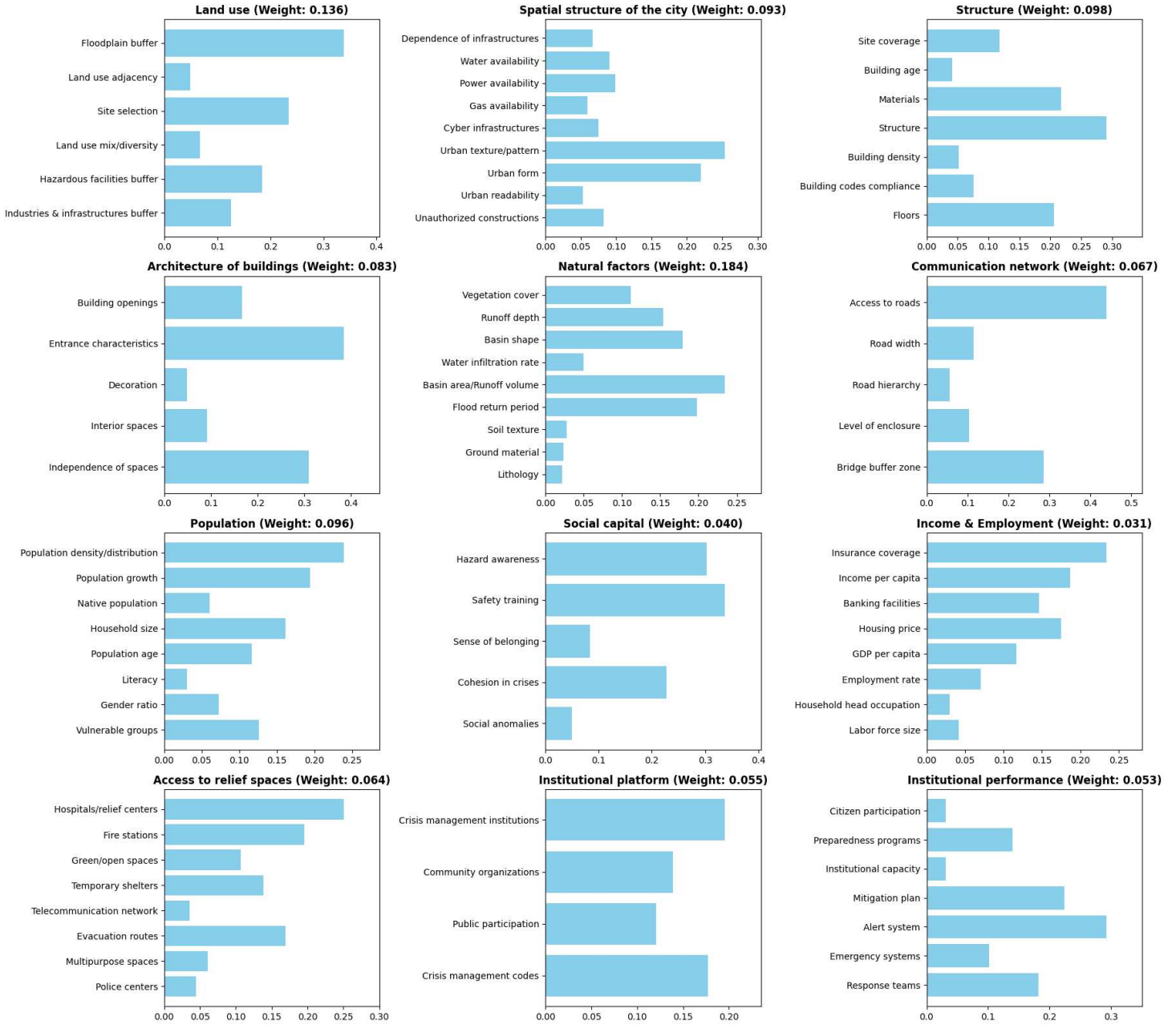


Figure 2. Obtained criteria weights

6. Sensitivity Analysis

Sensitivity analysis plays a crucial role in the verification of Multi-Attribute Decision-Making models (Demir et al., 2024). Sensitivity analysis not only depicts the robustness of the proposed methodology but also emphasizes the integrity of the obtained results. In this paper, two sensitivity analysis tests are designed to assess the robustness of the introduced model and the integrity of the

results. First, two other versions of the RANCOM model, Fuzzy RANCOM and crisp RANCOM, are considered to recalculate the final weights once more to observe the differences in criteria weighting process. Figure 3 shows the above-mentioned comparison.

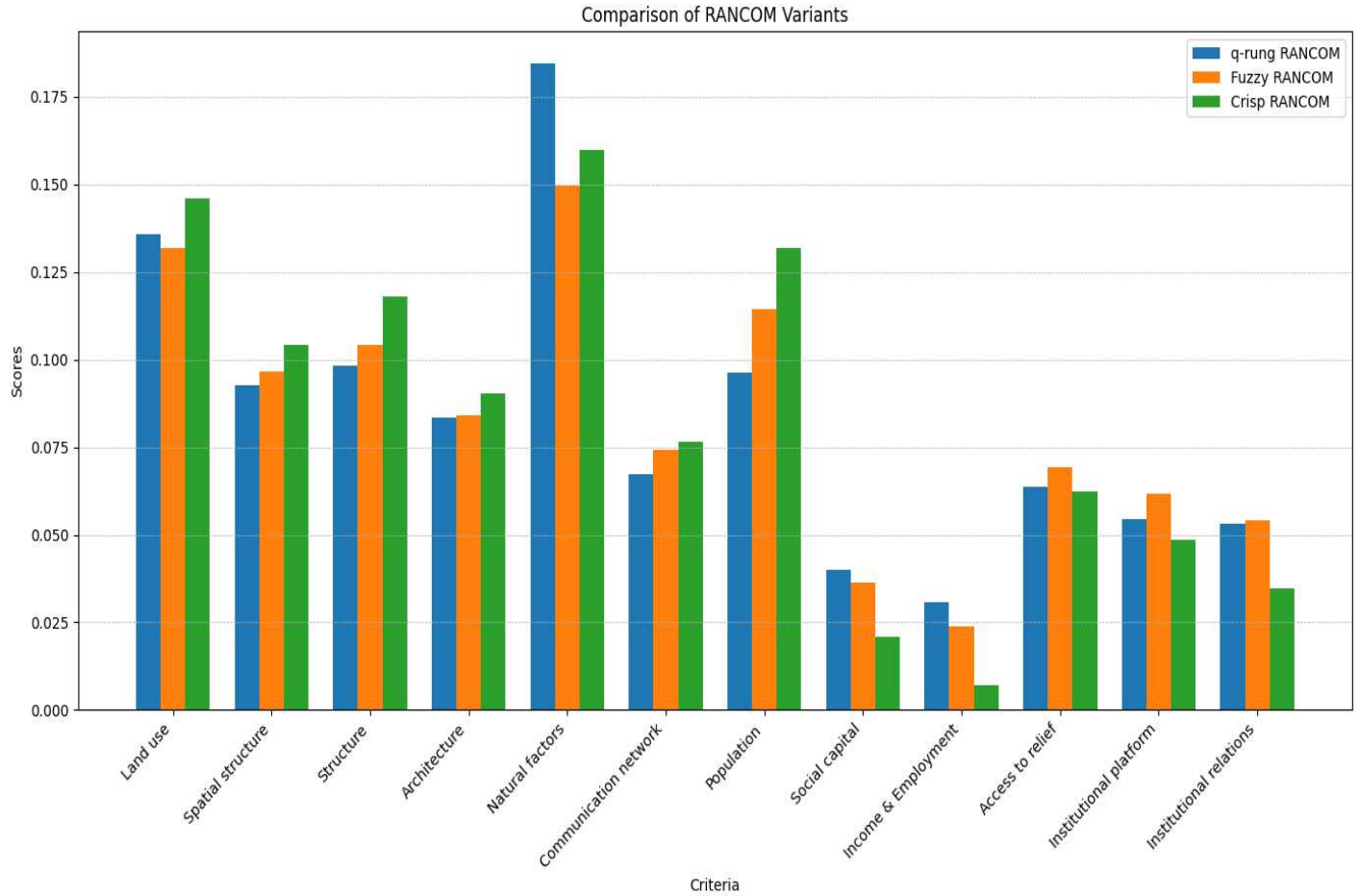


Figure 3. Criteria weights comparison

In addition, the pearson correlation coefficient test has also been utilized to solidify the results obtained. The oucomes are shown in Figure 4.

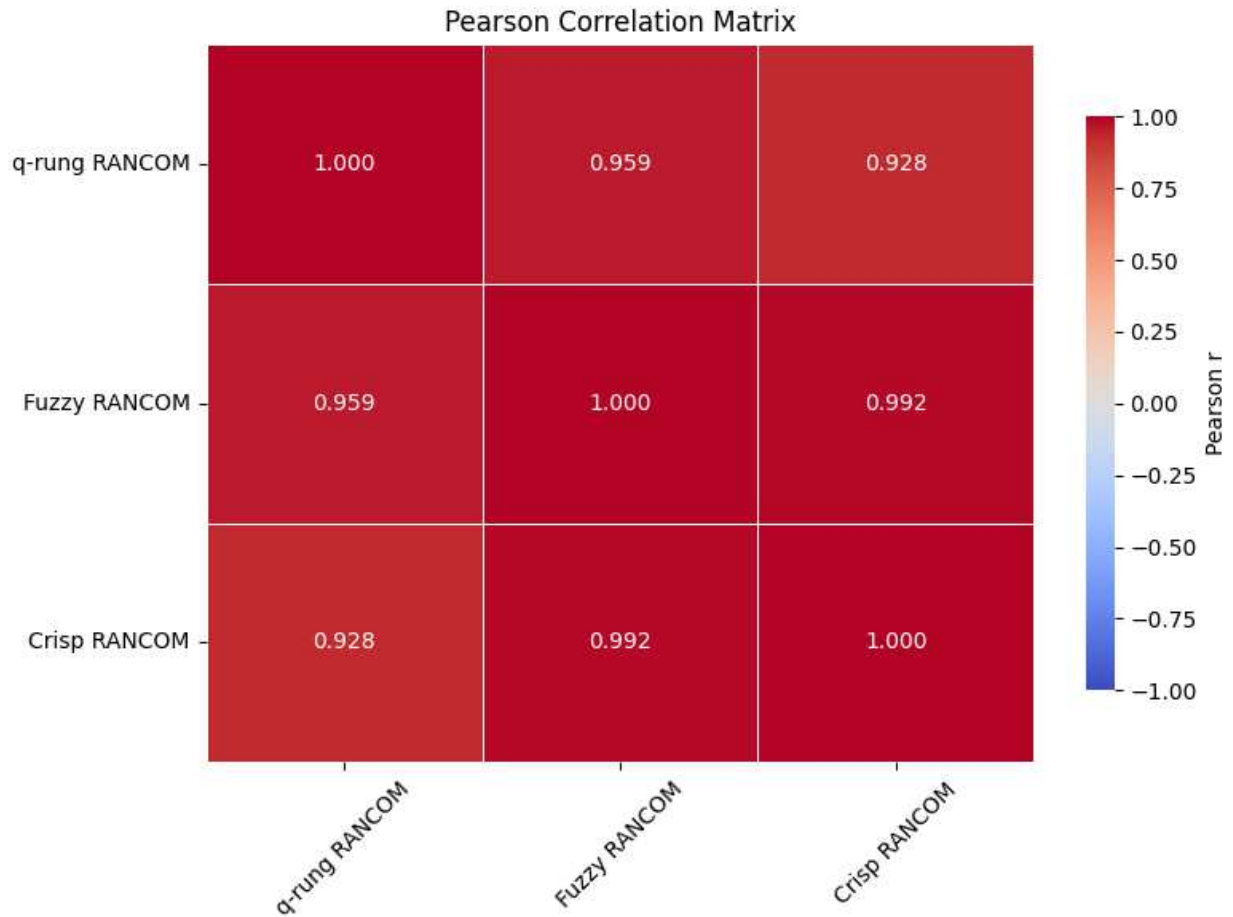


Figure 4. Pearson correlation coefficient test

Based on the results from the comparison of criteria weights and the Pearson correlation coefficient test, the newly introduced model in this research is sustainable and performs well when considering significant inputs of criteria and sub-criteria, while accounting for the possible uncertainty of human judgment. Specifically, the implementation of the Pearson correlation coefficient test clearly exhibited that the weights are trustworthy since there is no meaningful discrepancy between the obtained results of the three versions of RANCOM, including the one developed in this research. This experiment demonstrates that the method is capable of effectively handling expert uncertainty. Furthermore, the similarity between results indicates that the obtained rankings are robust, providing confidence that the outputs from this MADM approach can be reliably implemented in GIS-based decision-making applications.

7. Case study

Tehran is the 24th largest metropolitan area in the world, with a population of around 16 million in the Greater Tehran area. The city itself has approximately 9.8 million residents, which makes it the most populous city in Iran and Western Asia. The mountains to the north of Tehran overlook the city, and this mountainous terrain influences the drainage system.

District 5 of the municipality, covering an area of 5,287.1 hectares, is situated in the northwest of Tehran. This district is one of the 22 largest districts in Tehran. Currently, District 5 comprises seven areas and 29 neighborhoods. It is known as the development district of Tehran, experiencing increased population growth and urbanization largely due to its satisfactory location, which attracts residents from the central and southern parts of the city.

Moreover, District 5 is home to three rivers: the Kan River, which is the main river in Tehran, faces threats from seasonal and sudden floods each year and has the largest basin in the city. The Farahzad River, a tributary of the Darakeh in the northwest, flows westward into the Kan River, approximately two kilometers south of Zibahshahr town, and the Hesarak River, which is referred to as the Vesk River in its southern section. As a result, assessing the resilience of both Tehran and specifically District 5 is crucial for addressing flood resilience in urban areas as a comprehensive case study.

Figure 5 shows the spatial distribution of the resilience of District 5 of Tehran against floods. Details of each resiliency stage are provided in the supplementary file.

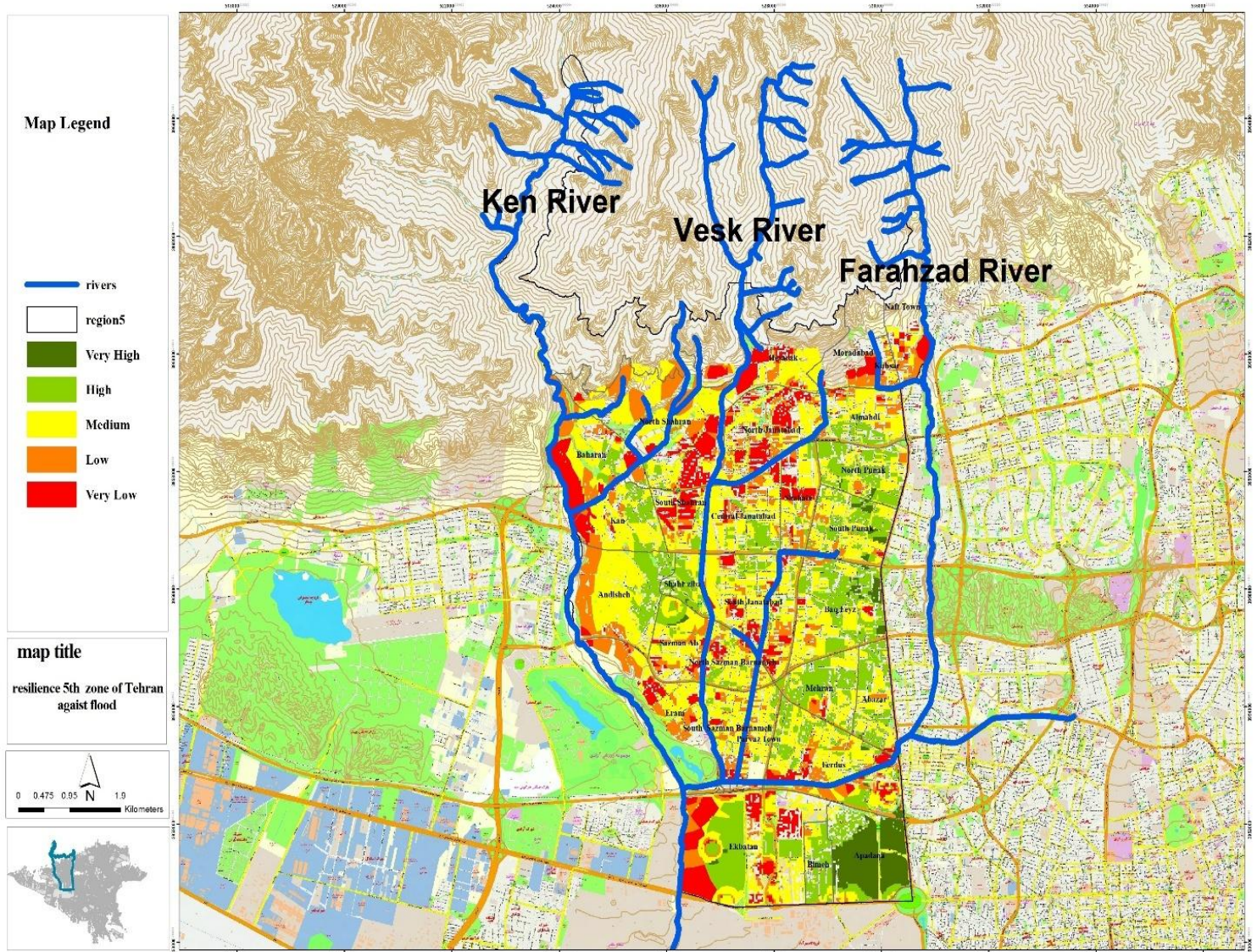


Figure 5. Resilience map of District 5 of Tehran metropolitan

The results of the resilience map show that 4.58% of the district has very high resilience, 16.73% has high resilience, 54.11% has moderate resilience, 11.60% has low resilience, and 12.98% has very low resilience. The neighborhoods of Janat Abad South, Punak South, Bagh Faiz, Mehran, Abazar, and the southern part of Ferdows neighborhood are of high resilience, and the neighborhoods of Shahr North and South, Janat Abad North, Shahrin, Planning and Budget Organization North, Ekbatan, Baharan, and Eram are also of low resilience.

8. Managerial Implications

Resilience in urban areas against floods can be obtained through three interconnected managerial strategies, which include defense, avoidance, and adaptation approaches. Each of the mentioned scenarios introduces distinct pathways for improving flood readiness, while together they form a comprehensive understanding of a resilience framework applicable to both developing and developed urban contexts.

The defense scenario centralizes on fortifying existing assets and populations through structural and non-structural benchmarks. The defense framework incorporates strengthening drainage networks, building retention basins, stabilizing riverbeds, and operating engineered flood barriers. Over and above the infrastructure, integrating green infrastructure such as vegetated zones and wetlands can both absorb excess water and mitigate downstream risks. Thus, this scenario enhances robustness for urban districts where moderate to high resilience already exists, which ensures that critical facilities such as hospitals, schools, and major transportation networks may remain functional during flood events.

The second approach is named the avoidance scenario, which underlines preventive land use planning and long-term urban development strategies that reduce exposure to hazards. Avoidance scenario structured on executing zoning restrictions in flood-prone vicinities, relocating vulnerable settlements, and securing proper setbacks from rivers and floodplains, to assist cities in preventing the accumulation of risk in future development. The scenario mentioned is mainly practical for rapidly growing urban districts, where uncontrolled expansion near riverbeds and low-lying areas often gives rise to potential vulnerabilities. Furthermore, utilization of the avoidance approach in urban management may not only reduce future disaster costs but also create opportunities for sustainable land use, such as parks, agricultural zones, and green corridors that would operate as natural barriers while a flood occurs.

The adaptation scenario recognizes that the complete elimination of flood risks is unrealistic and instead focuses on living with water. This interdisciplinary approach comprises publicizing resilient building designs, such as elevated structures and flood-resistant materials, and establishing community-level early warning systems, along with encouraging household preparedness measures such as movable flood barriers simultaneously. Adaptation is also social at its core, mandating awareness campaigns, participatory risk mapping, and the development of local response networks. Targeting neighborhoods with limited capacity for large-scale infrastructure

interventions, this scenario empowers communities to reduce vulnerability through behavioral and small-scale technological measures.

The three approaches introduced in this study can give rise to a layered resilience strategy, when defense criteria secure vital infrastructure, avoidance strategies reduce future exposure, and adaptation empowers local communities to comprehend the existing environmental risk and prepare themselves both mentally and physically. Miraculously, when combined, they transform resilience planning from a reactive response into a proactive governance approach, ensuring that resilience assessments and decision-making models are transformed into actionable urban policies.

Based on the comprehensive scenarios mentioned, it is suggested that:

- Buildings should have concrete floors and replace materials such as MDF and plasterboard with more durable ones.
- Providing movable obstacles in the form of vegetation in the path of flood risk.
- Providing special flood water storage tanks for streets with high flood risk.
- Residential areas under construction next to the river should be at a proper distance from it.
- Stopping and prohibiting the development of gardens and sustainable agricultural activities with long-term productivity in the riverbed and observing special rules next to the river.
- Controlling the exploitation of pastures and vegetation in the Ken basin and regenerating the destroyed pastures to reduce the risk of flooding.

The six suggestions mentioned previously were tested as a managerial scenario to mitigate the flood impacts and resilience metric improvement. Figure 6 illustrates the recalculation of resilience criteria after implementing the solutions.

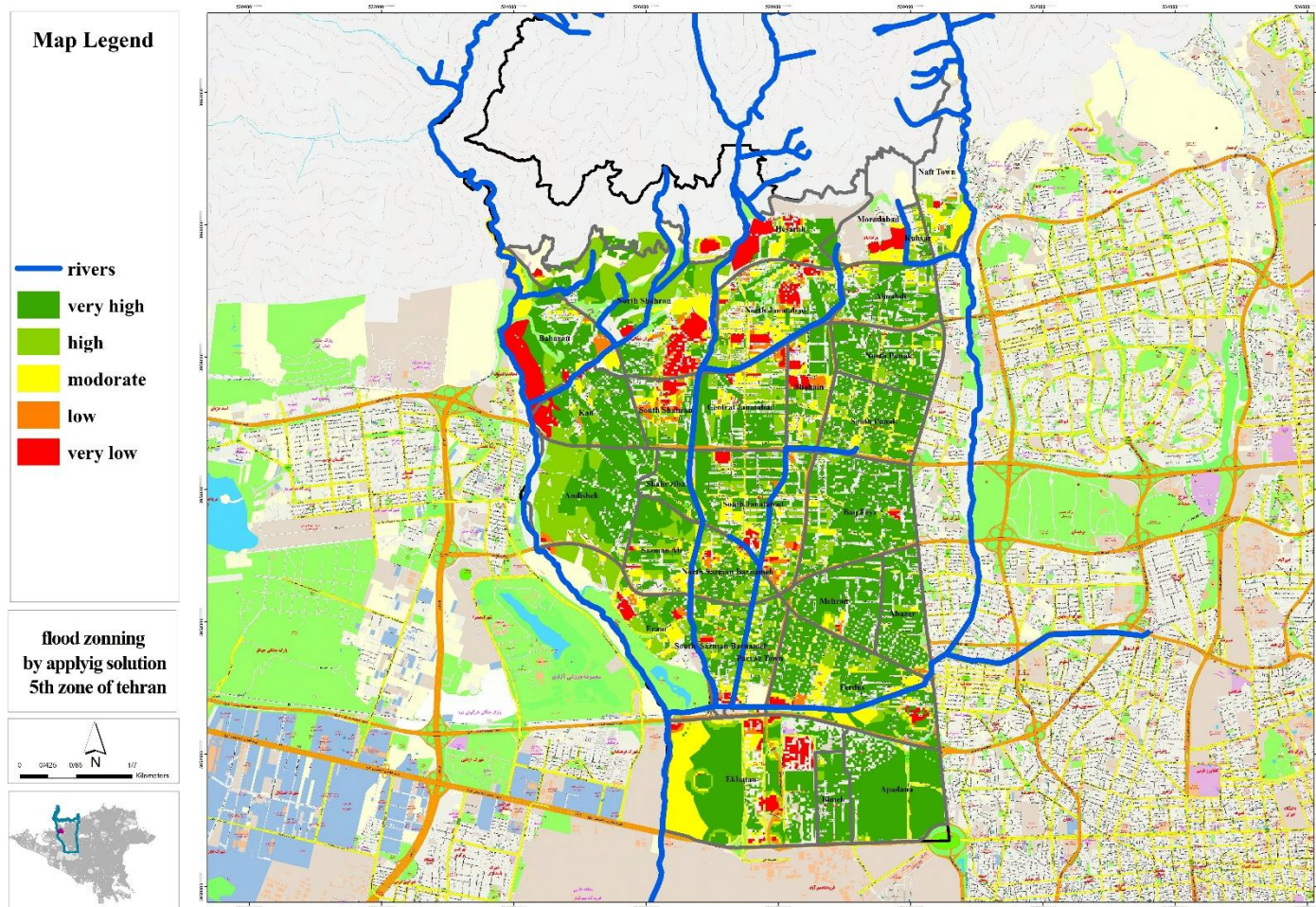


Figure 6. Resilience map after managerial scenario implementation

When comparing the case study area's resilience before and after implementing the flood resilience enhancement strategies, the results show a significant improvement. After the strategies were put in place, about 75.89% of the region reached high or very high resilience levels, a substantial increase compared to the much lower rate observed beforehand.

9. Discussion & Conclusion

Natural phenomena are considered one of the main elements of human disease and catastrophes in the current situation of the planet, and with climate change occurring, natural hazards follow this transition. In the current research, a novel decision-making model has been developed based on 12 main criteria and 81 sub-criteria to draw a road map for resilience assessment of urban districts against natural hazards, specifically floods. The model developed in this paper utilizes pairwise

comparison of the RANCOM model under uncertainty of human judgment using q-rung orthopair fuzzy sets integrated with GIS mapping.

The uncontrolled growth and development of the Tehran metropolitan and the inefficient drainage network highlight the need to address the problem of urban floods. District 5 of Tehran has been affected by floods and the resulting damage recently. As a result, the criteria weights, which were obtained in this research, were imported to the GIS to assess the resiliency of District 5 of Tehran and draw its resilience maps against floods. The western area of Tehran, particularly the region west of Kan, is at a higher risk of flooding during rainy periods compared to other parts of the city. Major highways, including Fath, Shahid Lashgari, Hakim, Shahid Kharazi, and Vardavard, exhibit low resilience to floods. These areas are particularly vulnerable to rainfall runoff due to the lack of key surface water networks or flood mitigation ponds. Such infrastructure is essential for redirecting and calming floodwaters at specific points before channeling them to designated areas. High-risk flood zones are primarily located downstream of the Farahzad basin, corresponding to its main valley. Overall, as one moves from the upstream northern section of the basin to the downstream southern section, the flood risk increases.

The results indicated that floodplains and areas adjacent to rivers are tremendously exposed to the dangers of floods. In addition, it was concluded that 4.58% of the district has very high resilience, 16.73% has high resilience, 54.11% has moderate resilience, 11.60% has low resilience, and 12.98% has very low resilience. Furthermore, a sensitivity analysis approach based on criteria weight comparison and Pearson correlation coefficient was implemented to evaluate the robustness of the introduced methodology, which concluded successful results.

Finally, three management scenarios have been considered for further suggestions on reducing vulnerability to floods. First, defense strategies against floods, second, strategies related to avoiding flood risk areas, such as relocation, which is mainly in the form of urbanization, and third, strategies related to living with the risk of flooding while preparing the local communities and maintaining an adequate level of awareness.

Declarations

This research has received no funding.

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Appendix A.

Table A.1 Experts' opinions and weights evaluation for the main criteria

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	μ_sum	ν_sum	S_i	W_i
C_1	E	VH	H	H	L	VH	VH	H	H	H	H	H	1.798	1.085	4.535	0.136
C_2	VL	E	VL	H	VL	H	L	H	H	H	VH	H	1.581	0.952	3.089	0.093
C_3	VL	H	E	H	VL	H	VL	H	H	H	VH	H	1.615	0.979	3.274	0.098
C_4	VL	VL	VL	E	VL	VH	VL	H	H	H	H	H	1.525	0.914	2.783	0.083
C_5	H	VH	H	H	E	VH	H	VH	VH	VH	VH	VH	1.984	1.183	6.154	0.184
C_6	VL	VL	VL	L	VL	E	VL	H	H	H	H	H	1.419	0.85	2.243	0.067
C_7	L	H	H	H	VL	H	E	H	H	H	H	H	1.611	0.988	3.217	0.096
C_8	VL	VL	VL	VL	VL	L	VL	E	H	L	VL	VL	1.172	0.65	1.335	0.040
C_9	VL	VL	VL	VL	VL	VL	VL	L	E	VL	VL	VL	1.063	0.559	1.026	0.031
C_{10}	VL	VL	VL	VL	L	L	L	H	H	E	H	H	1.388	0.819	2.125	0.064
C_{11}	VL	VL	VL	VL	VL	VL	L	H	H	L	E	H	1.314	0.766	1.819	0.055
C_{12}	L	L	VL	VL	VL	L	L	H	H	VL	L	E	1.294	0.736	1.768	0.053

Table A.2 Experts' opinions and weights evaluation for the first set of sub-criteria

	C_1	C_2	C_3	C_4	C_5	C_6	μ_sum	ν_sum	S_i	W_i
C_1	E	VH	VH	VH	VH	VH	1.640	0.985	3.455	0.338
C_2	VL	E	VL	L	VL	VL	0.869	0.536	0.502	0.049
C_3	E	VH	E	VH	H	VH	1.480	0.944	2.401	0.235
C_4	VL	H	VL	E	VL	VL	0.970	0.612	0.683	0.067
C_5	VL	VH	VL	VH	E	H	1.347	0.822	1.889	0.185
C_6	VL	VH	VL	H	VL	E	1.188	0.732	1.284	0.126

Table A.3 Experts' opinions and weights evaluation for the second set of sub-criteria

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	μ_sum	ν_sum	S_i	W_i
C_1	VL	VL	L	L	L	L	E	H	H	1.729	0.975	4.244	0.067
C_2	VL	VL	L	E	H	H	H	H	H	1.942	1.171	5.717	0.090
C_3	VL	VL	E	H	H	H	H	H	H	2.008	1.229	6.235	0.099
C_4	VL	VL	L	L	L	L	L	E	H	1.652	0.900	3.782	0.060
C_5	VL	VL	L	L	L	E	H	H	H	1.803	1.044	4.721	0.075
C_6	E	VH	VH	VH	VH	VH	VH	VH	VH	2.733	1.634	16.054	0.254
C_7	VL	E	VH	VH	VH	VH	VH	VH	VH	2.602	1.546	13.920	0.220
C_8	VL	VL	L	L	L	L	L	L	E	1.572	0.819	3.334	0.053
C_9	VL	VL	L	L	E	H	H	H	H	1.874	1.109	5.212	0.082

Table A.4 Experts' opinions and weights evaluation for the third set of sub-criteria

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	μ_sum	ν_sum	S_i	W_i
C_1	E	VH	VL	VL	H	H	L	1.296	0.792	1.680	0.118
C_2	VL	E	VL	VL	L	VL	VL	0.907	0.540	0.589	0.041
C_3	VH	VH	E	E	H	VH	VH	1.601	1.002	3.098	0.217
C_4	VH	VH	VH	E	VH	VH	VH	1.740	1.040	4.143	0.290
C_5	E	H	VL	VL	E	L	VL	1.036	0.716	0.745	0.052
C_6	L	H	VL	VL	H	E	VL	1.121	0.693	1.076	0.075
C_7	VH	VH	VL	VL	VH	VH	E	1.552	0.927	2.942	0.206

Table A.5 Experts' opinions and weights evaluation for the fourth set of sub-criteria

	C_1	C_2	C_3	C_4	C_5	μ_sum	ν_sum	S_i	W_i
C_1	E	VL	VH	H	VL	1.166	0.730	1.196	0.166
C_2	VH	E	VH	VH	VH	1.526	0.925	2.762	0.384
C_3	VL	VL	E	VL	VL	0.788	0.517	0.351	0.049
C_4	L	VL	H	E	VL	0.964	0.620	0.658	0.091
C_5	VH	L	VH	VH	E	1.420	0.862	2.223	0.309

Table A.6 Experts' opinions and weights evaluation for the fifth set of sub-criteria

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	μ_sum	ν_sum	S_i	W_i
C_1	E	VL	VL	H	VL	VL	VH	VH	VH	2.183	1.688	5.593	0.111
C_2	H	E	L	H	VL	VL	VH	VH	VH	2.364	1.762	7.741	0.154
C_3	VH	H	E	VH	VL	VL	VH	VH	VH	2.471	1.824	9.019	0.179
C_4	VL	VL	VL	E	VL	VL	VH	VH	VH	1.898	1.631	2.499	0.050
C_5	VH	VH	H	VH	E	H	VH	VH	VH	2.638	1.873	11.787	0.235
C_6	VH	VH	H	VH	VL	E	VH	VH	VH	2.516	1.815	9.948	0.198
C_7	VL	VL	VL	VL	L	VL	E	H	VH	1.76	1.593	1.409	0.028
C_8	VL	VL	VL	VL	VL	VL	VL	E	H	1.68	1.529	1.167	0.023
C_9	VL	VL	VL	VL	VL	VL	VL	L	E	1.656	1.511	1.092	0.022

Table A.7 Experts' opinions and weights evaluation for the sixth set of sub-criteria

	C_1	C_2	C_3	C_4	C_5	μ_sum	ν_sum	S_i	W_i
C_1	E	VH	VH	VH	VH	1.526	0.925	2.762	0.439
C_2	VL	E	H	L	L	0.99	0.631	0.719	0.114
C_3	VL	VL	E	VL	VL	0.788	0.517	0.351	0.056
C_4	VL	H	VL	E	L	0.964	0.62	0.658	0.105
C_5	VL	VH	H	VH	E	1.33	0.82	1.801	0.286

Table A.8 Experts' opinions and weights evaluation for the seventh set of sub-criteria

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	μ_sum	ν_sum	S_i	W_i
C_1	E	VH	VH	VH	VH	VH	VH	VH	1.830	1.088	4.841	0.239
C_2	L	E	VH	H	VH	VH	VH	VH	1.710	1.021	3.936	0.194
C_3	VL	VL	E	VL	VL	VH	VL	VL	1.152	0.678	1.217	0.060
C_4	VL	VL	H	E	VH	VH	VH	VH	1.608	0.961	3.270	0.161
C_5	VL	VL	H	L	E	VH	VH	H	1.447	0.872	2.367	0.117
C_6	VL	VL	VL	VL	VL	E	VL	VL	0.914	0.530	0.615	0.030
C_7	VL	VL	H	VL	VL	VH	E	VL	1.230	0.736	1.462	0.072
C_8	VL	VL	VH	L	L	VH	VH	E	1.475	0.872	2.546	0.126

Table A.9 Experts' opinions and weights evaluation for the eight set of sub-criteria

	C_1	C_2	C_3	C_4	C_5	μ_sum	ν_sum	S_i	W_i
C_1	E	VL	VH	VH	VH	1.407	0.856	2.158	0.303
C_2	H	E	VH	VH	VH	1.461	0.894	2.404	0.337
C_3	VL	VL	E	VL	H	0.936	0.609	0.594	0.083
C_4	L	VL	VH	E	VH	1.280	0.781	1.621	0.227
C_5	VL	VL	VL	VL	E	0.788	0.517	0.351	0.049

Table A.10 Experts' opinions and weights evaluation for the ninth set of sub-criteria

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	μ_sum	ν_sum	S_i	W_i
C_1	E	VH	VH	VH	VH	VH	VH	VH	1.830	1.088	4.841	0.234
C_2	VL	E	VH	H	VH	VH	VH	VH	1.701	1.017	3.870	0.187
C_3	VL	VL	E	VL	VH	VH	VH	VH	1.564	0.929	3.024	0.146
C_4	VL	VL	VH	E	VH	VH	VH	VH	1.662	0.988	3.626	0.175
C_5	VL	VL	VL	VL	E	VH	VH	VH	1.452	0.861	2.423	0.117
C_6	VL	VL	VL	VL	VL	E	VH	H	1.230	0.736	1.462	0.071
C_7	VL	VL	VL	VL	VL	VL	E	VL	0.914	0.530	0.615	0.030
C_8	VL	VL	VL	VL	VL	VL	H	E	1.030	0.618	0.857	0.041

Table A.11 Experts' opinions and weights evaluation for the tenth set of sub-criteria

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	μ_sum	ν_sum	S_i	W_i
C_1	E	VH	VH	VH	VH	VH	VH	VH	1.830	1.088	4.841	0.250
C_2	E	E	VH	VH	VH	H	VH	VH	1.705	1.055	3.782	0.196
C_3	VL	VL	E	VL	VH	VL	H	VH	1.380	0.825	2.067	0.107
C_4	VL	VL	H	E	VH	VL	VH	VH	1.503	0.899	2.669	0.138
C_5	VL	VL	VL	VL	E	VL	VL	L	0.943	0.544	0.678	0.035
C_6	VL	VL	VH	H	VH	E	VH	VH	1.608	0.961	3.270	0.169
C_7	VL	VL	L	VL	H	VL	E	H	1.145	0.695	1.165	0.060
C_8	VL	VL	VL	VL	H	VL	VL	E	1.030	0.618	0.857	0.044

Table A.12 Experts' opinions and weights evaluation for the eleventh set of sub-criteria

	C_1	C_2	C_3	C_4	μ_sum	ν_sum	S_i	W_i
C_1	E	VH	VH	VH	1.392	0.855	2.072	0.196
C_2	VL	E	H	VL	0.9	0.606	0.506	0.139
C_3	VL	L	E	VL	0.779	0.528	0.326	0.121
C_4	VL	VH	VH	E	1.245	0.773	1.468	0.177

Table A.13 Experts' opinions and weights evaluation for the tewelfth set of sub-criteria

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	μ_sum	ν_sum	S_i	W_i
C_1	E	VL	E	VL	VL	VL	VL	0.89	0.644	0.438	0.031
C_2	VH	E	VH	VL	VL	H	VL	1.364	0.824	1.978	0.139
C_3	E	VL	E	VL	VL	VL	VL	0.89	0.644	0.438	0.031
C_4	VH	VH	VH	E	VL	VH	H	1.596	0.96	3.181	0.224
C_5	VH	VH	VH	VH	E	VH	VH	1.74	1.04	4.143	0.292
C_6	VH	L	H	VL	VL	E	VL	1.226	0.742	1.434	0.101
C_7	VH	VH	VH	VL	VL	H	E	1.489	0.897	2.580	0.182