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ORIGINAL RESEARCH PAPER

Optimal fire station site selection: A Fuzzy-GIS Multi-Criteria hybrid approach

H. Karbalaie[1,*], F. Izadbin[2]

[1] Department of RS & GIS, Faculty of Geography, University of Tehran, Tehran, Iran

[2] Department of Environmental Planning, Management & Education, Faculty of Environment, University of Tehran, Tehran, Iran

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ABSTRACT

BACKGROUND AND OBJECTIVES: Cities, with their complex infrastructures and diverse services, require a scientific and principled approach to strategic site selection for service provision. Fire stations represent one of the most essential urban services, and inadequate research and planning for their site selection and distribution in many cities significantly increase risks to urban residents' safety and well-being. District 8 of Karaj faces rapid population growth and urban development, highlighting the urgent need for a strategic expansion of fire stations. This study aimed to propose a novel approach to assist in the optimal site selection of fire stations in this area.

METHODS: This study employed a novel hybrid method combining the Stepwise Weight Assessment Ratio Analysis method and Fuzzy logic with ArcGIS techniques. This integration aimed to minimize ambiguity in weighting criteria and improve the accuracy of site selection decisions. The 11 criteria were identified based on their impact on fire station efficiency and responsiveness, including industrial, commercial, storage, educational, and healthcare centers, as well as filling stations, residential areas, gathering places, road networks, population density, and office buildings. The final desirability map was created by overlaying weighted fuzzy layers in ArcGIS, visually highlighting optimal locations.

FINDINGS: The weighting analysis showed that industrial centers (0.1131) held the highest weight in fire station site selection, while educational centers (0.0735) had the lowest. The final spatial desirability map revealed that 24% of the northern and southwestern areas of District 8 had high suitability for fire station placement. The southwestern area, despite the high operational statistics at Fire Stations 125 and 3 (55%), lacks adequate fire coverage. To address this issue, three potential sites were identified in the high-desirability zone in the southwestern region, with a field survey evaluating neighborhood compatibility, access to networks, and recent urban developments.

CONCLUSION: This study presents a robust framework for optimizing fire service operations in District 8 of Karaj. Through this framework, the region was classified into five categories of desirability for fire station placement. Additionally, the analyses uncovered the unequal distribution of emergency services across the district. The results facilitated the identification of three suitable sites to enhance fire service provision. Given the effectiveness of this methodology, the study strongly recommends that urban planners adopt this innovative framework for emergency site selection, emphasizing the importance of addressing response needs and spatial factors, such as high-density areas and accident-prone centers.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
31	8	2

*Corresponding Author:
Email: *H.karbalaie@ut.ac.ir*
Phone: +989369992359
ORCID: 0009-0003-3148-3316

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INTRODUCTION

Fires can be a great threat to human beings, the built environment, and nature, causing injuries, deaths, economic loss, and pollution (Yao *et al.,* 2019). Fires cause up to 180,000 deaths globally per year; this is more than triple the annual average number of fatalities due to all-natural hazards (Moullier *et al.,* 2020). Over 95% of fire-related deaths and injuries occur in low- and middle-income countries, with incidents in built-up areas rising sharply due to rapid urbanization (Abrassart *et al.,* 2024). As urbanization, climate change, and technological advancements intensify, the risks of fire-related disasters increase, making effective fire prevention and emergency response plans essential (Khalid, 2024). Reasonable construction and strategic placement of fire facilities and stations significantly enhance the government's ability to mitigate or prevent fire-related disasters in urban areas (Lai *et al.,* 2011). However, many cities have an insufficient number of fire stations with heavy workloads (Tao *et al.,* 2022). In rapidly growing cities like Karaj, these challenges are particularly pronounced. District 8 of Karaj, characterized by dense residential developments and the concentration of critical facilities, has experienced rapid urbanization. This unplanned growth, coupled with insufficient fire station coverage, has resulted in significant gaps in emergency response capabilities, leaving the area highly susceptible to fire-related disasters. The basic requirement for improving rescue operations in cities is determining the optimal location for fire department facilities (Macit, 2015). However, the decision-making process for urban land use allocation has always been complex (Arefiev, 2015). Optimal site selection for fire stations demands comprehensive spatial data analysis and a thorough understanding of the spatial relationships that influence emergency response requirements. To address these challenges, Malczewski (2006) suggests that integrating Geographic Information Systems (GIS) with Multiple-Criteria Decision-Making (MCDM) approaches is an effective solution, enabling decision-making based on geographic data and indicator prioritization. Taking advantage of information technology, GIS enables the handling of both spatial and nonspatial data, leading to its specific roles in data management and integration, data query and analysis, and data visualization (Cheng *et al.*, 2007). Moreover, fuzzy set techniques can be utilized in GIS modeling to account for the inherent uncertainty in real-world land-use systems (Grekousis *et al.,* 2012). Despite these strengths, GIS techniques alone exhibit limitations in determining the weights of criteria necessary for site selection. Consequently, these techniques are often paired with MCDM methods to enhance their decision-making capabilities. Among MCDM methods, the Stepwise Weight Assessment Ratio Analysis (SWARA) approach stands out. It is a structured approach that involves breaking down complex decision-making problems into simpler parts and assigning weights to each criterion to determine their relative importance (Akram *et al.,* 2023). This method is an expert-oriented approach to determining the weights of criteria and can be effectively combined with GIS techniques to solve complex location problems. This hybrid approach can provide a more objective and systematic way of making decisions compared to traditional approaches based on intuition or subjective opinions (Ghobadi, 2023). Various studies have examined the optimal fire station site selection methods and criteria. Amlashi (2019) examined the role of fire station placement in enhancing urban safety by employing the Analytic Hierarchy Process (AHP) method with GIS. This study employed AHP to assign weights to criteria, which were subsequently integrated through overlay analysis in ArcGIS to determine ideal sites for fire stations. Nyimbili and Erden (2020) conducted a study to effectively plan the location of emergency facilities for proper service delivery in Istanbul, Turkey. They proposed a fuzzy-AHP approach for the optimal site selection of fire stations. The weights obtained from this approach were validated with the Best-Worst MCDM technique (BWM), which was compatible. In a study, Lai *et al.,* (2011) combined GIS and AHP methods to determine the layout of firefighting facilities and argued that this approach offers greater flexibility and universality, significantly reducing the complexity of site selection. In addition to research focused on fire station site selection, several studies have examined the site selection of various urban services. The application of diverse GIS and MCDM methods in these studies can enhance the process of selecting optimal locations for fire stations. Zandi *et al.,* (2024) focused on creating a hospital site suitability map, considering socio-environmental factors and combining GIS with MCDM weighting methods. This study employs the Best-Worst Method (BWM) and SWARA to enhance the suitability analysis of hospital sites. Sensitivity analysis revealed that the GIS-based SWARA-Weighted Linear Combination (WLC) model was the most stable and effective approach for determining hospital site suitability in the study area. Da Silva Romero *et al.,* (2023) focused on developing a multi-criteria model that integrates GIS and fuzzy logic to identify suitable areas for the implementation of biorefineries. They compared the created model with the middle center and Boolean logic models and claimed that the GIS-FUZZY model provides better results than other models. In a study to select a landfill site, Ghobadi (2023) proposed a GIS-based SWARA method in the east of Lorestan province, Iran. He stated that the proposed method provides decision-makers with a systematic approach to evaluating and ranking potential sites based on their suitability. Wang *et al.,* (2022) used a location decision model based on GIS and improved TOPSIS to locate integrated energy stations in Tianjin, China. This study develops an evaluation index system covering nature, economy, and society, using the AHP method to calculate index weights. The GIS overlay function integrates related layers, and the improved TOPSIS model ranks the alternatives to determine the optimal choice. The literature shows that while various MCDM methods and GIS techniques are commonly used for facility and infrastructure site selection, advanced methodologies for fire station site selection remain underutilized. This is despite the inherently complex nature of decision-making required for urban emergency services. Among these methods, the SWARA method stands out due to its ability to integrate complex spatial relationships and expert judgment. When combined with fuzzy logic techniques in GIS, SWARA provides urban planners with a powerful tool for optimizing fire station placement, potentially offering advantages over traditional approaches. District 8 of Karaj is rapidly expanding, with new constructions, industrial centers, and institutions such as hospitals and universities attracting a growing population. To meet the increasing demand, expanding emergency services, especially by adding fire stations, is crucial. However, few studies have focused on selecting optimal sites for fire stations in this area, and existing research has several limitations. First, previous studies often relied on a narrow set of criteria, failing to capture the complexities of the urban system that are essential for effective fire station site selection. They also overlooked important spatial characteristics that are critical for efficient emergency response and fire station performance. Second, these studies did not incorporate advanced decision-making methods like the SWARA method, which enables better alignment with decision-making needs. This study addresses the critical need for improved fire station infrastructure in District 8 of Karaj by proposing a novel approach for site selection that integrates comprehensive criteria, the SWARA method, and fuzzy logic within ArcGIS techniques to optimize fire station placement in 2025.

MATERIALS AND METHODS

Description of the study area

Karaj, with a population of 1,592,000, is the fourth most populous city in Iran and a key destination for immigrants. District 8, located in the northeastern part of Karaj, has a population of 135,000. This area is characterized by diverse land uses, increasing construction activity, and heavy traffic during peak hours. The combination of these land uses has transformed the city into a multi-functional urban space, complicating the spatial relationships between them. Moreover, the presence of population-attracting centers, such as universities and healthcare facilities, underscores the need for fire infrastructure that can meet the region's growing demands. Fig. 1 illustrates the location of the study area and current fire stations. District 8 currently has three fire stations. Stations 3 and 129 are grand stations with advanced capabilities, while Station 125 is a small station with more limited resources. Despite the heavy traffic and notable accident and fire statistics in the southern part of District 8, Station 125's limited capacity often necessitates support from other stations during major incidents. Station 3, positioned on the boundary between Districts 8 and 7, is occasionally deployed to handle fires and accidents in District 7. In contrast, Station 129 benefits from a strategically advantageous location, with its central position, modern facilities, proximity to densely populated and sensitive areas, and easy access to the main road network significantly enhancing its effectiveness. A statistical analysis of fire station operations from 2020 to 2023 revealed that District 8 recorded a total of

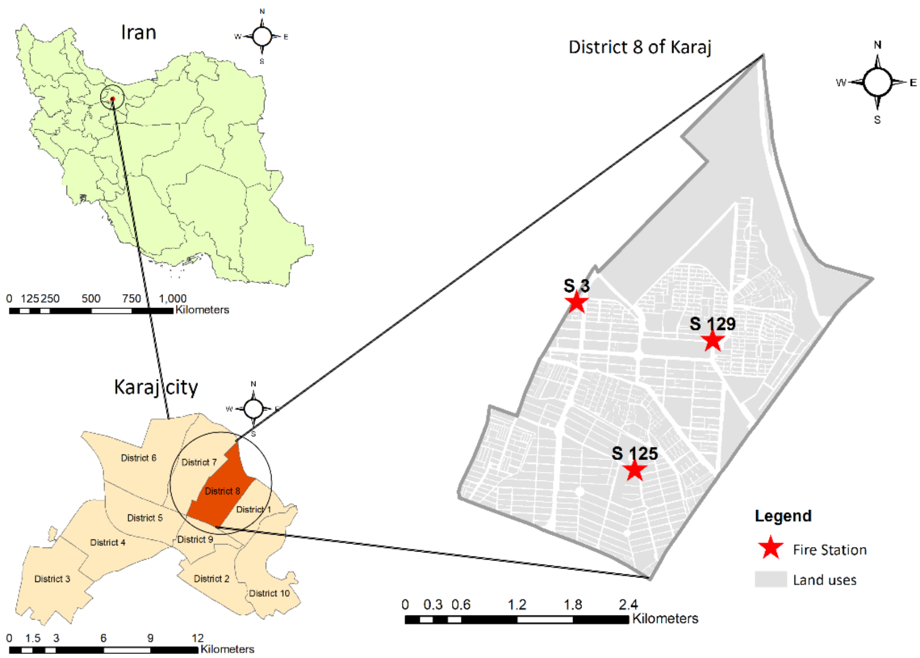

Fig. 1: Geographic location of the study area in District 8 of Karaj

2,412 missions related to incidents and fires. Among these, Station 129 responded to 706 missions, Station 125 to 909 missions, and Station 3 to 345 missions. Furthermore, fire stations located outside District 8 contributed to 371 missions within the district during this period. Fig. 2 provides a visual representation of the percentage of station involvement in missions from 2020 to 2023.

Development of the research process

The process of selecting optimal locations for fire stations using the SWARA fuzzy-GIS method was carried out in eight systematic steps, as illustrated in Fig. 3. Before initiating the methodological steps, a comprehensive assessment of the study area was conducted to define the research objectives and approach. This preliminary stage involved consultations with local firefighting experts, analysis of mission statistics, and an evaluation of existing resources and the operational capacities of current fire stations. Subsequently, in the first step, eleven criteria for fire station site selection were identified. These criteria were established through a review of relevant literature, adherence to regional fire station establishment standards, and expert opinions from fire services. In the second and third steps, the participating experts assigned weights to each criterion, with the final weights calculated using the SWARA method. The experts involved in this process were all professionals from the fire department, including both fire service specialists and active firefighters. The key criteria for fire station site selection are summarized in Table 1. The fourth step involved gathering, digitizing, updating, and modifying criteria-related documents and spatial layers in ArcGIS software. To ensure the accuracy of the spatial data, digitized layers were corrected and updated through the review of recent documents and satellite imagery. In the fifth step, each layer was transformed into a fuzzy raster by determining its fuzzy membership type based on the specific definition of each criterion. In the sixth step, the raster layers were weighted according to the SWARA findings. The seventh step involved generating an optimal location map through a fuzzy overlay of the 11 weighted and fuzzified layers. Finally, in the eighth step, a field survey was conducted to validate the map results and ensure the accuracy of the optimal locations. This survey assessed factors such as neighborhood compatibility and significant urban

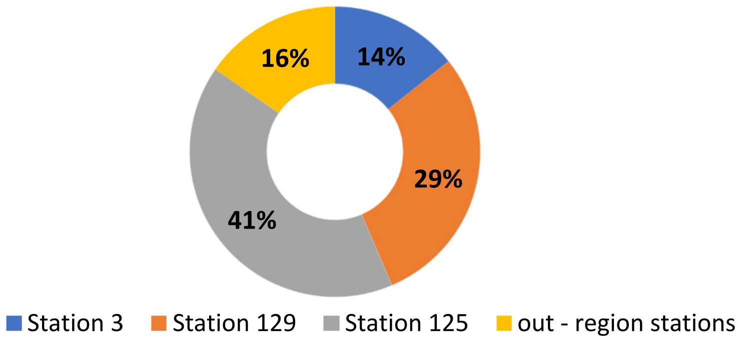

Fig. 2: The percentage of fire and accident missions of stations in Karaj District 8 from 2020 to 2023

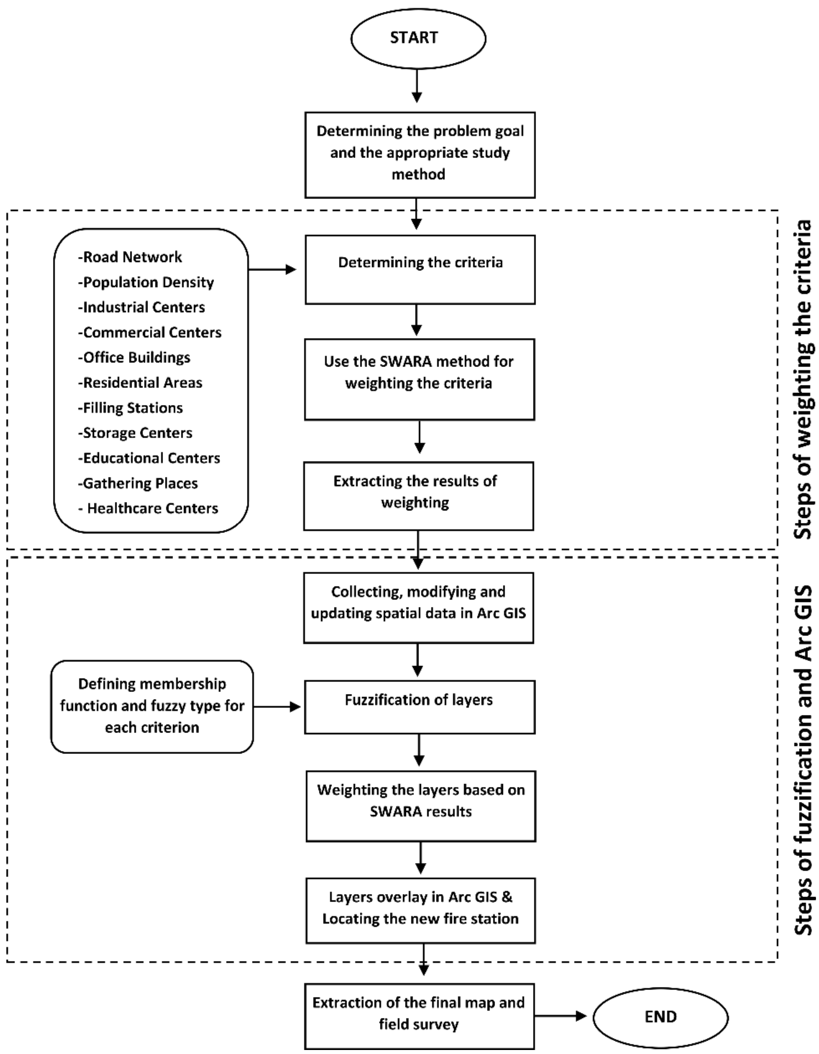

Fig. 3: Diagram of the research process

Table 1: Description of the suitability criteria

	Criteria	Suitability	Reference
C1	**Road Network**	Proximity to the main road and streets with a width of more than 15 meters.	Habibi *et al.,* (2008) Amlashi (2019) Erden and Coskun (2010) Ziari and Yazdan.P (2011) ISIRI (2001)
C2	**Population Density**	A denser population is prone to more accidents. One fire station for every 50,000 people.	Habibi *et al.* (2008) Amlashi (2019) Lai *et al.* (2011) Erden and Coskun (2010)
C3	**Industrial Centers**	Proximity to industrial centers due to flammable and chemical substances.	Johnson (1999) Habibi *et al.,* (2008) ISIRI (2001)
C4	**Commercial Centers**	Proximity to commercial centers that contain flammable materials such as plastic, cloth, and paper, and the presence of large crowds in places such as stores and markets.	Johnson (1999) Amlashi (2019) ISIRI (2001)
C5	**Office Buildings**	Proximity to office centers due to the gathering and movement of people and the use of flammable materials such as paper and electronic devices.	Johnson (1999) ISIRI (2001) Amlashi (2019)
C6	**Residential Area**	Proximity to neighborhoods with high housing density due to density in population, fuel, and food, which are flammable and prone to life and financial damage.	Johnson (1999) Amlashi (2019)
C7	**Filling Stations**	Proximity to gasoline and gas stations, which have a large volume of flammable materials and are prone to ignition and explosion, and due to providing services to the fire trucks.	Habibi *et al.* (2008) Amlashi (2019) Nisanci *et al.* (2012)
C8	**Storage Centers**	Proximity to storage centers due to the storage of a large amount of various flammable items.	Amlashi (2019) ISIRI (2001) Nisanci *et al.* (2012)
C9	**Educational Centers**	Proximity to these institutions is due to gathering in these places within a 500-meter limit. because these institutions have traffic at certain times of the day.	Johnson (1999) ISIRI (2001) Şen *et al.* (2011)
C10	**Gathering Places**	Proximity to gathering places within a 500-meter. In order not to disrupt the service of fire stations due to the traffic of gathering centers, restrictions should be placed on proximity to these centers.	Amlashi (2019) ISIRI (2001)
C11	**Healthcare Centers**	Proximity to medical centers with a 500-meter limit. Due to the sensitivity of healthcare centers to noise pollution and the presence of traffic around these centers.	Johnson (1999) Habibi *et al.* (2008) Amlashi (2019) ISIRI (2001) Nsaif and Al-Obaidi (2022)

changes to ensure the practical feasibility of the proposed fire station sites.

The criteria

The criteria for fire station site selection have been established based on a review of previous studies, expert opinions, and regional standards for fire station locations. The criteria are listed in Table 1. Every criterion had an impact on the effectiveness and responsiveness of fire stations as well as the necessity for fire services. A comprehensive understanding of each criterion's definition is essential as it encompasses key information, including its impact on the distance and proximity of fire stations, its compatibility with neighboring stations, and the evaluation of relevant limits. Fire stations are generally compatible with densely populated areas, industrial and commercial centers, and filling stations; however, they face compatibility challenges when located near healthcare and educational facilities due to traffic and congestion near these centers. It is important to consider regional standards when selecting and determining criteria in fire station site selection studies, as this ensures the maximization of the cost-benefit ratio for the community in the selection of suitable sites for specific land uses (Hailemariam, 2021). Therefore, in this study, the selection and determination of acceptable values for certain criteria have been based on regional standards.

Fuzzy-GIS Multi-Criteria method

The SWARA method provides an opportunity for policymakers to choose the best decision based on dissimilar situations and import criteria based on their wants and objectives (Majeed & Breesam, 2021). It is a completely judgmental method, and

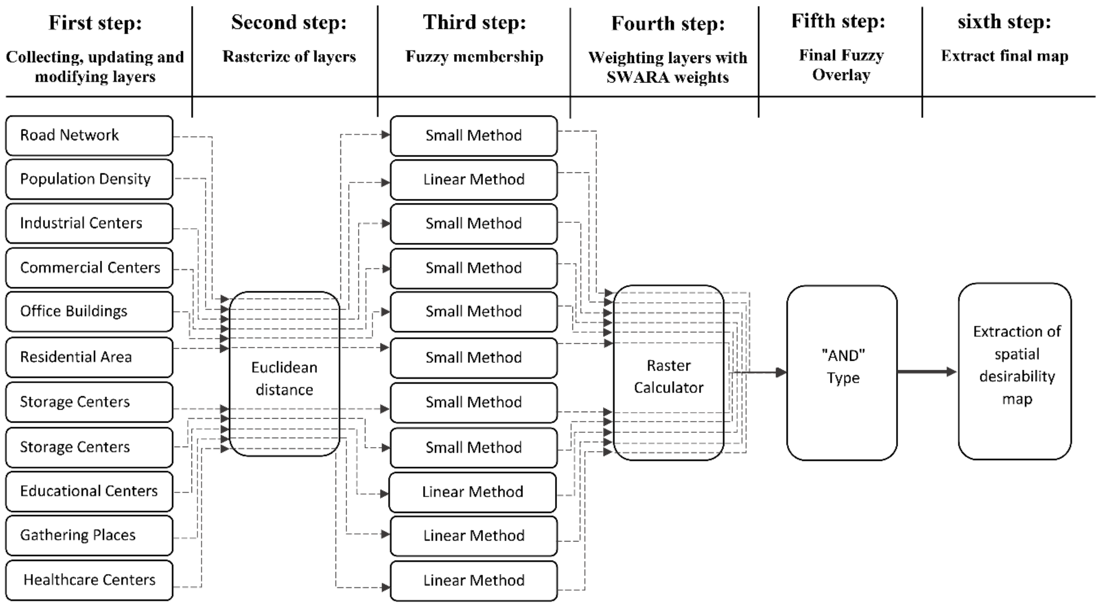

Fig. 4: Steps of fuzzification and Arc GIS

experts (respondents) play an important role in determining the weight of criteria; moreover, the number of pairwise comparisons has been reduced, and attention has been paid to the uncertainty in the evaluation (Dehshiri and Firoozabadi, 2023). These attributes make the SWARA method a powerful tool for spatial studies, enabling it to produce results that closely align with expert opinions and real-world conditions. In this study, the SWARA method has been employed for weighting the criteria for fire station site selection to ensure the final weights are highly consistent with expert opinions while minimizing ambiguity. The main steps for weighting based on the SWARA method are as follows:

1. Sorting the criteria:

Once the final criteria are identified, they are ranked based on their level of importance.

2. Comparative significance (Sj):

In this step, the relative importance of each criterion is assessed in comparison to the previous, more important criterion. This value is represented by Sj.

3. Calculating the coefficient (Kj):

The coefficient Kj reflects the relative importance of each criterion and is calculated using the following formula:

$$kj = Sj + 1$$

4. Calculating the initial weight of each criterion (Qj):

The initial weight of each criterion is determined using the formula:

$$Qj = Qj - 1 / Kj$$

5. Calculation of the final normal weight (Wj):

The final weight of the criteria, which represents the normalized weight, is computed using the following formula:

$$Wj = Qj / \sum \mathrm{Qj}$$

In addition to the appropriate selection and weighting of criteria, it is imperative to employ analytical tools and modeling techniques within ArcGIS software that more accurately represent the complex spatial relationships between criteria in the real world. In GIS, analytical functions and traditional cartographic modeling methods based on Boolean logic implicitly assume that objects

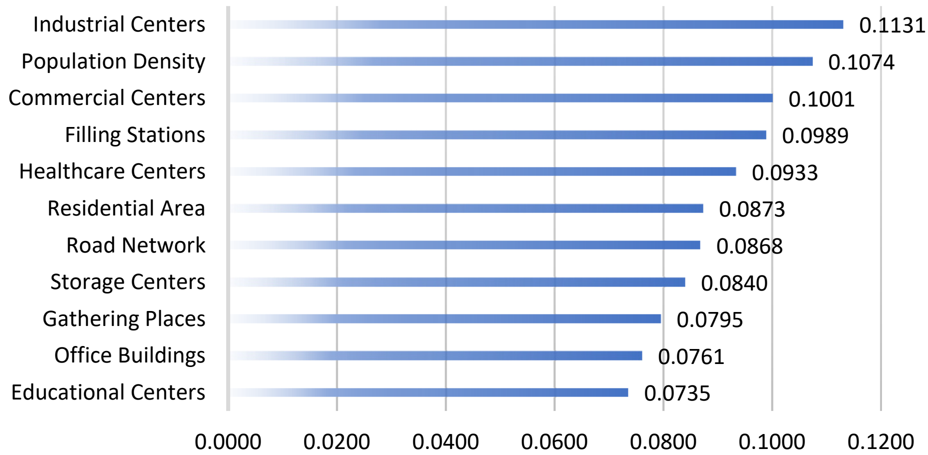

Fig. 5: The weight rating of criteria

in a spatial database and their characteristics are uniquely defined. However, the inherent constraints of classical set theory do not allow for partial set membership or imprecise information in GIS. The inadequacy of Boolean logic in representing and manipulating spatial data poses a significant obstacle to realistic GIS modeling (Sui, 1992). To better represent environmental issues in modeling, fuzzy logic provides a more nuanced approach than Boolean logic. By transforming data into a fuzzy raster set with membership grades, the degree to which each cell belongs to a specific feature can be assessed. Fuzzy operators and functions in ArcGIS software enable both *(1) scaling criteria according to each criterion's range*

(2) overlaying criteria as raster layers.

Given the aforementioned advantages, this study integrates fuzzy-GIS techniques with the SWARA method to effectively model spatial criteria and optimize the placement of fire stations in District 8. Fig. 5 illustrates the key steps in ArcGIS for creating a spatial desirability map, starting with data collection and ending with the production of the final map.

RESULTS AND DISCUSSION

The final weight of criteria in the SWARA method ranges from 0 to 1. Table 2 and Fig. 5 show the weight of each criterion according to experts' opinions and its final weight. Criteria such as industrial centers (weight: 0.1131) were assigned higher weights due to their critical role in fire station location planning, as these areas are associated with higher fire risks due to flammable materials, hazardous processes, and dense infrastructure. In contrast, criteria such as educational centers (weight: 0.0735) received lower weights, as schools generally pose lower fire risks and have fewer incidents compared to other centers evaluated in the study. Karaj District 8 is an urban area characterized by diverse land uses. The high weights assigned to industrial centers, commercial centers (weight: 0.1001), densely populated areas (weight: 0.1074), and filling stations (weight: 0.0989) in the weighting table reflect the concentration of factories, workshops, malls, and flammable materials in the region, all of which contribute to an increased risk of accidents and fires. Many fire station location studies overlook the diversity of land uses, neglecting not only the spatial relationships between these centers but also their service requirements and their impact on the response efficiency of fire stations. By integrating local characteristics into the analysis and weighting process, this approach provides a practical tool for optimizing fire station locations in Karaj District 8.

Raster layers of criteria

The rasterized maps of the 11 criteria, shown in Fig. 6, provide valuable insights into the spatial distribution of key factors influencing fire station

Table 2: Total weight of site selection criteria of fire stations based on SWARA method

	Criteria	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Weighted average
C1	Road Network	0.0595	0.1054	0.0565	0.0871	0.1023	0.1055	0.0913	0.0868
C2	Population Density	0.1095	0.1102	0.1083	0.1065	0.1023	0.1234	0.0913	0.1074
C3	Industrial Centers	0.1255	0.0890	0.1114	0.0992	0.1179	0.1234	0.1252	0.1131
C4	Commercial Centers	0.1095	0.0867	0.1035	0.0871	0.1108	0.1156	0.0874	0.1001
C5	Office Buildings	0.0695	0.0795	0.0614	0.0819	0.1108	0.0639	0.0657	0.0761
C6	Residential Area	0.0915	0.1035	0.0989	0.0871	0.0759	0.0739	0.0804	0.0873
C7	Filling Stations	0.1195	0.0906	0.0945	0.0949	0.0671	0.0947	0.1309	0.0989
C8	Storage Centers	0.1045	0.0795	0.0928	0.0856	0.0586	0.0739	0.0930	0.0840
C9	Educational Centers	0.0725	0.0676	0.0697	0.0841	0.0759	0.0844	0.0606	0.0735
C10	Gathering Places	0.0645	0.0676	0.1166	0.1001	0.0847	0.0464	0.0770	0.0795
C11	Healthcare Centers	0.0745	0.1205	0.0864	0.0864	0.0938	0.0947	0.0971	0.0933

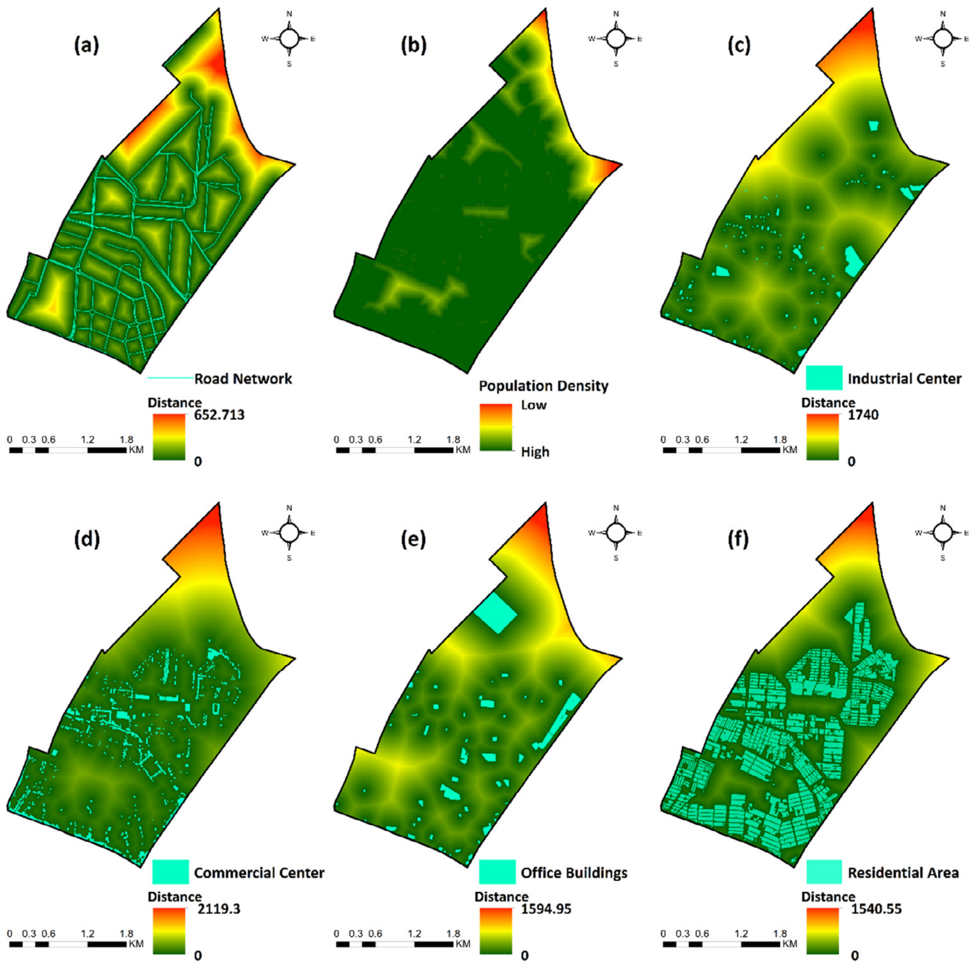

Fig. 6: Rasterized maps of criteria

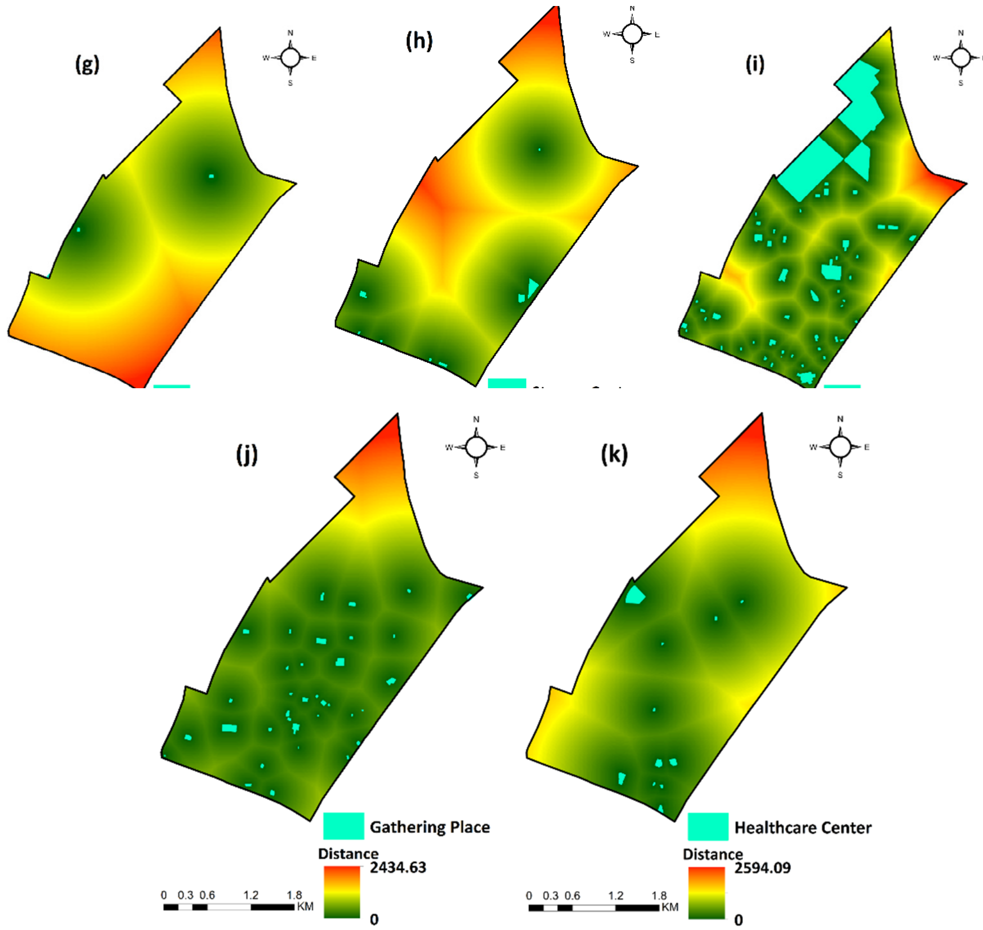

Fig. 6: Rasterized maps of criteria

placement in Karaj District 8. As depicted in Fig. 6(a), the northern areas, characterized by barren land and ongoing construction, have the least developed road network. Due to the lack of essential infrastructure and a comprehensive road system, this region is considered a lower priority for fire station placement. Fig. 6(b) shows that the northern and northwestern areas of the district have the lowest population density, indicating that fire stations may not be as critical in these regions. The spatial distribution of industrial centers (Fig. 6(c)) and commercial centers (Fig. 6(d)) is spread throughout District 8. Given the high weights assigned to these criteria in the weighting process, their dispersed distribution (except the northern area) underscores the importance of strategically positioning fire stations to ensure broad coverage and accessibility. Office buildings (Fig. 6(e)) and educational centers (Fig. 6(i)) were among the least weighted criteria in the fire station placement weighting process. Both are scattered across District 8 and exhibit lower fire risks compared to other sensitive areas. However, they must still be considered in fire station location planning due to the presence of flammable materials, vulnerable individuals, and the concentration of people within these facilities. A prominent feature of District 8 is the rapid development of residential areas, particularly in the center and southern parts of the district (Fig. 6(f)), driven by high migration rates. The presence of flammable materials in homes further emphasizes the importance of placing fire stations in proximity to these areas to reduce response times and mitigate fire risks. Filling stations, highlighted in Fig. 6(g), are in the northeastern and western parts of the district,

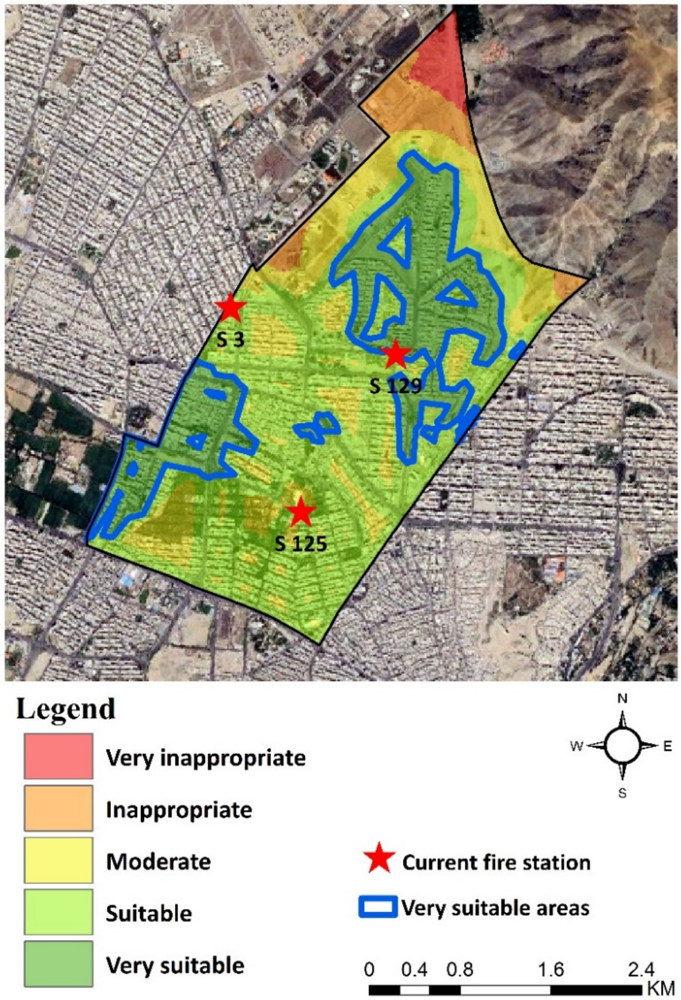

Fig. 7: Fire station suitability areas map

and Fig. 6(h) shows a concentration of storage centers in the southern and western regions. These areas, with their higher fire risks due to the constant accumulation of fuel, flammable materials, and the transportation of these substances, necessitate the presence of fire stations nearby to ensure rapid responses and minimize potential damage. District 8 of Karaj includes various gathering places, such as mosques and halls (Fig. 6(j)), which require fire stations due to the sensitivity of large crowds and flammable materials. To ensure optimal accessibility and response times, these centers should be situated at least 500 meters from fire stations, considering the traffic and congestion they generate at specific times. District 8 of Karaj hosts several major healthcare centers, as shown in Fig. 6(k), particularly in its central and southern areas. Due to factors such as population density, vulnerability of individuals, and the presence of flammable materials, these hospitals require nearby fire stations. To balance accessibility and operational efficiency, fire stations should ideally be located within a 500-meter radius of hospitals, considering visitor traffic and noise sensitivity. Given the nature of spatial relationships, the criteria are interdependent and mutually influence each other in determining the optimal locations for fire stations and the final suitability map. For example, in District 8 of Karaj, areas near densely populated, industrial,

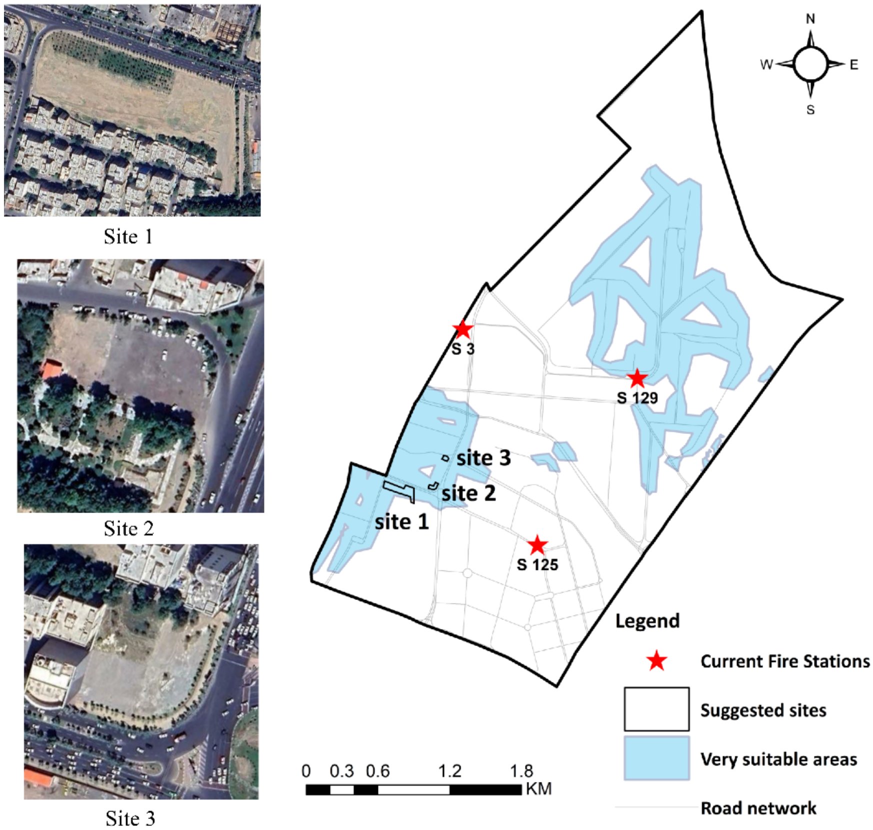

Fig. 8: Location of suggested sites

and commercial centers are prioritized by experts to enhance safety and reduce response times, thereby having a greater impact on the final suitability map. Additionally, centers with specific distance constraints to fire stations, such as hospitals and meeting centers, also play a significant role in the final analysis and station placement. By accounting for these interdependencies, a comprehensive framework for fire station placement can be developed for Karaj District 8, ensuring optimal coverage, accessibility, and safety across the region.

Suitable areas map

The final desirability map, shown in Fig. 7, was generated by overlaying the fuzzy-weighted layers of all criteria. This map classifies the study area into five suitability categories: very suitable, suitable, moderately suitable, inappropriate, and very inappropriate. The red regions represent areas least suitable for fire station placement, while the dark green regions indicate the most optimal locations. Highly suitable areas constitute 24.87% of the total area, followed by suitable areas at 48.38%, moderately suitable areas at 19.3%, inappropriate areas at 4.98%, and very inappropriate areas at 2.46%. Notably, two prominent zones classified as highly suitable are in the northern and southwestern parts of the district. These zones are strategically situated in proximity to critical infrastructure, including arterial roads, industrial hubs, commercial centers, and densely populated residential neighborhoods. An analysis of fire station mission statistics, along with a comparative review of the suitability map and the current distribution of fire stations in District 8, reveals a substantial gap between the region's emergency service needs and its existing infrastructure, particularly in the southwestern areas. The suitability map underscores the uneven distribution of emergency services and assists in identifying optimal locations for future fire stations. Leveraging these insights for the development of fire station infrastructure will enhance emergency response efficiency and mitigate fire risks in high-priority areas.

Determination of susceptible areas

This study identifies three strategic sites for the establishment of new fire stations in District 8 of Karaj, in the southwest region (Fig. 8). These areas were selected based on a comprehensive analysis of several criteria, including accident and fire statistics, population density, and critical facilities. The southwest zone stands out due to its proximity to densely populated residential areas, industrial complexes, and commercial centers, which create an elevated demand for emergency services. The selected sites in the southwest align with the suitability map generated using the SWARA GIS-Fuzzy model, which considers urban development patterns, accessibility to main roads, and proximity to high-risk areas. These sites were confirmed through field visits and spatial evaluations, ensuring they met critical planning requirements and addressed existing service gaps. By enhancing response times and improving coverage in high-risk zones, these proposed sites aim to bolster the district's firefighting infrastructure and overall resilience to fire-related emergencies.

Limitations and future research

To address the limitations of this study, which focused on the optimal site selection of fire stations to improve emergency response, it is important to acknowledge that the lack of open access to reliable databases from relevant governmental organizations posed significant challenges. Specifically, sensitive data, such as population density, could not be obtained with the level of accuracy required. Given the dynamic nature of population changes, up-to-date data was critical for precise decision-making. Unfortunately, the study had to rely on available, less accurate data due to this limitation. To mitigate this issue, the researchers conducted additional validation procedures using calculations from other data sources. While this study utilized a Fuzzy-GIS SWARA model, future studies could refine this approach by integrating real-time traffic patterns, temporal variations in population density, and other dynamic factors. Additionally, for regions prone to natural disasters, it would be beneficial to include specific risks, such as proximity to earthquake fault lines, in the site selection process. These targeted improvements could enhance the precision and applicability of emergency response planning, ensuring that fire stations are optimally located to handle both everyday incidents and extraordinary events.

CONCLUSION

This study investigated the optimal placement of fire stations in Karaj District 8 to improve emergency response capabilities. By combining SWARA and fuzzy techniques within the ArcGIS framework, a comprehensive model for fire station site selection was developed. The research identified 11 key criteria influencing the need for fire station services, including industrial centers and densely populated areas, which were found to be the most critical factors. Educational centers and office buildings were deemed less impactful. The suitability map showed that 24.87% of District 8 was highly suitable for fire station placement, with the northern and southwestern regions being the most optimal. To address the pressing needs in the southern to western areas, three potential sites for a new fire station were proposed in the highly suitable southwestern region (Fig. 8). The hybrid methodology used in this study effectively addresses the complexities of fire station site selection in District 8 of Karaj, providing urban planners with a reliable tool to align firefighting infrastructure with the increasing service demands and challenges posed by population growth and urban development in the region. The final analysis of the current distribution of fire infrastructure and service needs provides crucial guidance for addressing the unequal allocation of emergency services throughout the district. To address the disparities in firefighting coverage, resource allocation should prioritize establishing auxiliary fire stations in high-demand areas, such as the southwestern region, to enhance emergency response capabilities. Additionally, engaging local communities and key stakeholders, including owners of high-risk facilities and industries as well as officials from organizations influencing fire station operations, during the planning stages can help ensure that new fire facilities are aligned with neighborhood needs and integrated into broader urban development strategies. The SWARA Fuzzy-GIS approach offers superior capabilities compared to existing methods, particularly in reducing uncertainty and improving decision-making accuracy for fire station site selection. Its ability to integrate spatial criteria and account for their complex interrelations makes it highly adaptable to diverse emergency site selection contexts. This model's flexibility underscores its potential for broader application across various regions and urban planning scenarios. This study recommends that urban planners, crisis managers, and other stakeholders adopt efficient methods, including the model presented here, for the planning, implementation, and evaluation of fire station site selection. Future research should expand this model's application to other regions, integrating dynamic factors like real-time traffic patterns, population changes, and the impact of fire station rankings.

AUTHOR CONTRIBUTIONS

H. Karbalaie contributed to the literature review, collected relevant documents and spatial data related to the selection criteria, created GIS maps, analyzed the spatial data, and was responsible for writing and editing the manuscript. F. Izadbin contributed to the literature review, applied the SWARA weighting method, gathered operational statistics, and consulted with experts from the Karaj Fire Department.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely witnessed by the authors.

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ABBREVIATIONS

AHP	Analytic Hierarchy Process
BWM	Best-Worst MCDM technique
GIS	Geographic Information Systems
ISIRI	Iran National Standards Organization
Kj	Coefficient value
MCDM	Multiple-Criteria Decision-Making
Qj	Initial weight
SWARA	Stepwise Weight Assessment Ratio Analysis
SPP	Solar Power Plant
Sj	Comparative significance value
Wj	Final normal weight

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