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Optimal Fire Station Site Selection in Erbil City, Kurdistan Region of Iraq: A GIS-AHP Approach

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Abstract: In a rapidly sprawling city with population growth, as Erbil city, the Kurdistan Region of Iraq (KRI), the placement of fire stations can make a major difference in how quickly emergency services respond. This study looks at how Geographic Information System (GIS) tools, combined with the Analytic Hierarchy Process (AHP), can be used to identify the best areas for building new fire stations. Fourteen Parameters were considered, including population density in each area, the risk of disasters, proximity to roads, and where current fire stations are located. Experts helped assign importance to each factor using the AHP method. All the data were processed in GIS to create a map showing which parts of the city are most suitable and essential. The map revealed five categories of suitability, with the eastern and southern districts, especially the neighborhoods in Municipalities 3, 4, and 5-marked as high-priority zones. These cover nearly 46% of the study area. A Receiver Operating Characteristic (ROC) analysis was done, resulting in an Area under the Curve (AUC) of 0.910, which shows strong accuracy for the AHP technique. Overall, the results show that using this method helps make more informed decisions about emergency planning. It can be concluded that the same approach could be useful in other cities facing similar problems with how emergency services are distributed, and the study shows a good decision for urban planners to consider where to establish new emergency facilities in future planning.

Keywords: *Fire Station Site Selection; Urban Emergency Planning; Erbil City; GIS; AHP.*

1. Introduction

The optimum placement of fire stations is critical to the objective of urban safety and efficiency of emergency support systems, which can decrease the response time, safety, and availability in the event of emergencies and can save lives [1]. The proper selection of sites for Fire Stations in rapidly expanding urban centers, such as in the case of Erbil City, has been determined by high population density, urbanization, and growth of industrial zones, and over the past few years, urban fires have been progressively rising as a result of heightened conflicts between the environment, resources, and the urban population [2]. Regular fires have a major negative impact on economic growth and pose direct or indirect risks to human life [3].

Unplanned urban expansion and ineffective administration were responsible for the annual increase in disaster-related destruction in urban areas. Most of deaths occur in low- and middle-income nations, with urban areas being especially vulnerable because they are typically found in high-risk areas and have higher occupation densities [4]. Rapid urbanization, heightened competition for land, steadily declining vegetation cover, changes in land use, and greater natural environment variability are the causes of this. This problem is exacerbated by the fact that urban management is frequently reactive to disasters and rarely considers prevention, as there is a lack of information and resources on pre-disaster plans and preventive initiatives because of technical, institutional, and financial efforts concentrated on post-disaster actions [5].

Determining the best locations for fire stations is a complex problem that presents daunting complexity. Urban planners must evaluate many factors, such as the accessibility of roads to the site, conformance of the use of land with the area, proximity to dangerous places, existing base population, and future capacity for growth. A rigorous framework for decision-making capable of accommodating a variety of potentially contradictory points is required to effectively weigh these factors [6].

In recent years, Geographic Information Systems (GIS) have become valuable tools in urban facility planning so that urban planners can visualize and evaluate possible sites in-depth owing to GIS's ability to integrate and analyze both spatial and non-spatial data. A Geographic Information System (GIS) can objectively assess several criteria and, using expert judgment, assign relative importance to each criterion when paired with Multi-Criteria Decision Analysis (MCDA) techniques, particularly the Analytic Hierarchy Process (AHP) [7]. Fire stations are among the many urban facilities whose placement has been optimized by this integration [8, 9].

It has good features to use GIS with decision-making frameworks such as AHP, in efforts to arrive at optimal facility sitting. [10] used GIS-MCDA model to identify centers for emergency logistics demonstrating the flexibility and specificity of the approach at the spatial decision analysis. [6] showed that GIS and AHP can be successfully integrated to find the best locations for fire stations in Wuhan, China, and that this is a practical solution that might be applied to other cities.[11] showed how GIS-supported MCDA and AHP can be utilized to make decisions regarding site locations for wastewater infrastructure, demonstrating the applicability of the method for various infrastructure projects.[12] reviewed many studies on the GIS-AHP, indicating the capability of the technique to act in difficult spatial situations and improve the quality of decision-making. Although these methodologies have demonstrated promising possibilities, research on fire station planning within the dynamic urban context of Erbil is rather limited.

Although GIS-MCDA procedures are becoming more widely used worldwide, they are rarely used in Erbil for choosing fire station locations. These methods were only used in one relevant article published in 2014 [13] and the findings were aimed at that period rather than the urban life of this century. Erbil's rapid urbanization and population expansion have increased the demand for more cutting-edge site-specific decision-making tools, as Erbil’s new urbanization is not well suited to the current fire station design, and certain areas are not adequately covered, as shown in Figure 1. To improve the emergency response capabilities in Erbil, structured analytical techniques must be used to address the misalignment between the current fire station placement and urban dynamics.

This study attempted to develop a GIS-aided AHP model to identify the desired locations for new fire stations in Erbil City. The specific study objectives are:

1. To identify and describe the main factors for selecting suitable locations for fire stations in Erbil’s urban setting.
2. The relative importance of each criterion was measured using an Analytic Hierarchy Process (AHP).
3. Integrate the criteria weights with GIS technology for integrated multi-criteria assessment.
4. To produce a suitability map that highlights the best locations for future fire station placement.

By fulfilling these goals, this research is intended to assist urban planners and emergency management authorities with the development of a sturdier fire safety network and provide services in a comprehensive manner to the Erbil community.

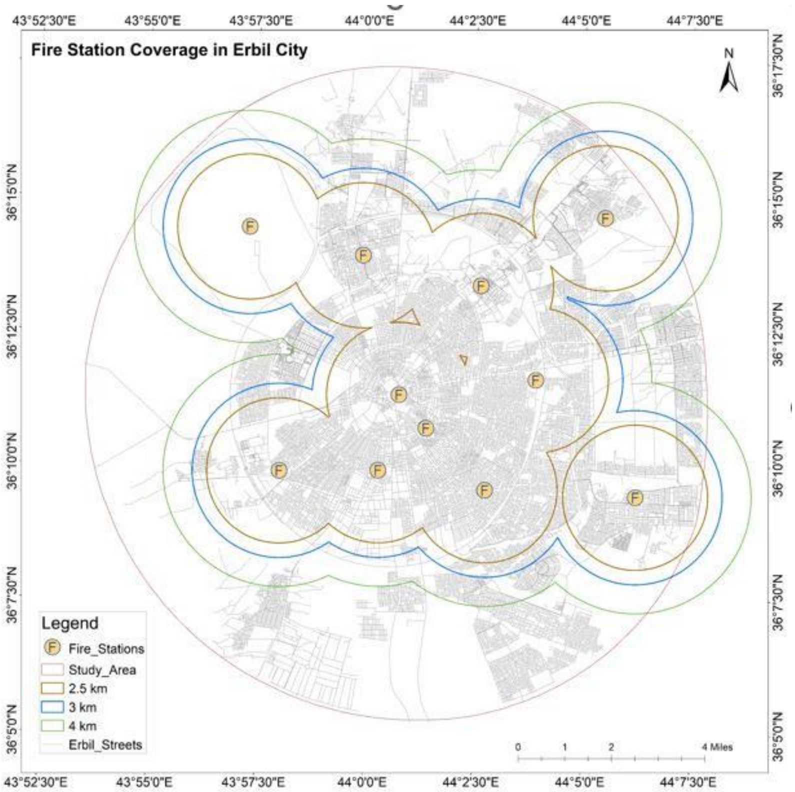

Figure 1: Current distribution of fire stations in Erbil City, with corresponding service areas represented by three different buffer zones.

2. Methodology

2.1 Study Area

Urban expansion in Erbil, the capital city of the Iraqi Kurdistan region, has grown rapidly in the last two decades, resulting in massive structural transformation and land-use practices in the city. In 2018, the city's built-up area had grown to 291.80 km2 from 118.9 km^2 in 2000, mostly due to political stability and economic recovery after 2003 [14]. This change has concentrated the population, infrastructure, and services in the city center, especially inside the 150-meter ring road, which is a strategically important area that is thought to be the administrative and commercial center and spans approximately 364 km^2. Research shows that urbanization and population growth have decreased green spaces and raised the need for public services [15]. The 150-meter ring boundary serves as the basis for the study area used in this study, which focuses on the densely populated city where emergency response coverage is crucial Figure 2. The semi-arid climate and growing urban density, as well as deteriorating public services in the Erbil Center, pose additional problems in managing disasters in general, particularly fire control and emergency access [16-18].

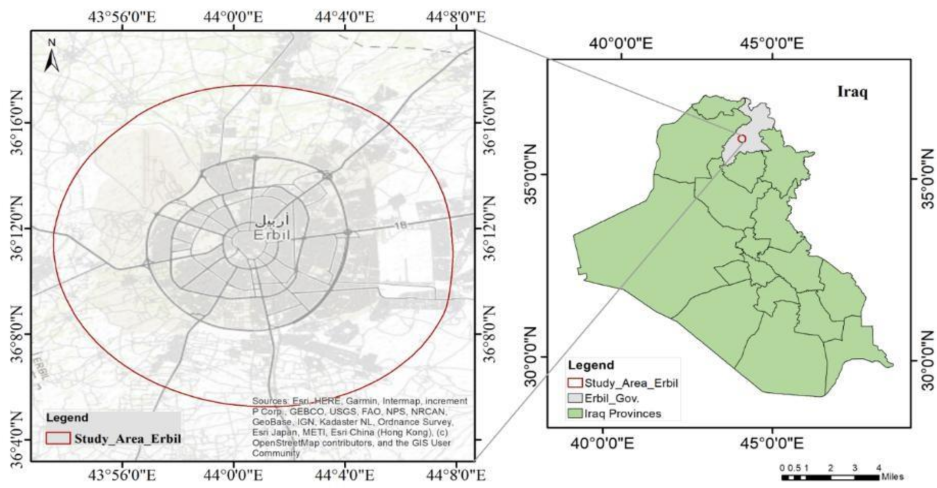

Figure 2: Map of the Erbil City (within the 150 Meter Ring Road)

2.2 Data Sources and Preparation

The criteria in this research were purposely selected based on extensive considerations of the factors that influence the effective stationing of fire stations, including physical constraints, the environment, infrastructure, and expenditures. Fourteen distinct datasets were included in the analysis. A slope layer was derived from a Digital Elevation Model (DEM) with a 12.5-meter resolution, sourced from the Alaska Satellite Facility (ASF), to represent topographical constraints. Key infrastructure layers, including road networks, public service locations, and proximity to major roads, were obtained primarily from OpenStreetMap (OSM) and processed using ArcMap.

Population data were drawn from previous urban studies and cross-referenced with the 2024 projections provided in [19]. Specific criteria, such as distances to hospitals, schools, fuel stations, parks, police stations, commercial areas, and multistory buildings, were developed through spatial analysis using OSM data. The distance from industrial districts and existing fire occurrences helped determine relevant risk factors. Information on the existing fire stations was collected from the Erbil Civil Defense Directorate and verified through field surveys. All spatial datasets were standardized to the same projection system (UTM Zone 38N) and a 12.5-meter resolution for uniformity. A summary of all datasets and their sources is provided in Table 1.

Table 1: Criteria and data sources used in the study

Types of Data	Criteria	Description	Source
Socio- Economic	Population Density (PD)	Prioritized areas with higher population density using projected 2024 data	Previous Studies & https://krso.gov.krd/en/statistics/population
	Proximity to Educational Institutions (EI)	Distance to educational institutions including schools, colleges, and kindergartens to prioritize emergency response	Erbil Governorate (Sepember-2024)
	Proximity to Hospitals & Health Centers (HHC)	Distance to hospitals and health centers for coordinated medical emergency response	Ministry of Health MOH-Kurdistan (September-2024)

	Proximity to Police Stations (PC)	Proximity to police stations to enhance coordination between fire and law enforcement agencies	OpenStreetMap (OSM) (December 2024) https://www.openstreetmap.org
	Proximity to Commercial Compound Areas (CA)	Distance to commercial hubs such as banks, shopping centers, and restaurants	OpenStreetMap (OSM) (December 2024) https://www.openstreetmap.org & Field Survey Verifications
	Proximity to Multi- story Building Areas (MBA)	Proximity to high- density residential areas requiring increased emergency preparedness	OpenStreetMap (OSM) (December 2024) https://www.openstreetmap.org & Field Survey Verifications
Geographical	DEM (Slope) (SL)	Derived from DEM to represent topographical constraints	https://asf.alaska.edu/
Risk-Related	Proximity to Industrial Areas (IA)	Proximity to industrial zones with higher fire risk	OpenStreetMap (OSM) (December 2024) https://www.openstreetmap.org
	Proximity to Fire-Incident Zones (FID)	Proximity to historical fire incidents to prioritize high-risk areas	Erbil Civil Defense Directorate / Field survey (2020-2024)
	Proximity to Fuel Stations (FS)	Distance to fuel stations to ensure logistical support during emergencies	OpenStreetMap (OSM) (December 2024) https://www.openstreetmap.org
Infrastructure-Related	Proximity to Main Roads (PRD)	Euclidean distance to primary roads for accessibility and rapid response	OpenStreetMap (OSM) (December 2024)
	Distance from Existing Fire Stations (EFS)	Distance to existing fire stations to avoid redundancy and improve coverage	Erbil Civil Defense Directorate / Field survey (October-2024)
	Proximity to Built-up Areas (BUA)	Classification of built-up and open areas	Microsoft: https://planetarycomputer.microsoft.com/dataset/ms-buildings, OpenStreetMap: https://data.humdata.org/dataset/hotosm irq_buildings
	Proximity to Parks and Playgrounds (PPG)	Proximity to public parks and playgrounds to ensure safety in recreational spaces	OpenStreetMap (OSM) (December 2024) https://www.openstreetmap.org

2.3 Methodology and Criteria Selection

The methodology of this study primarily relied on literature and expert opinions to assign 14 parameters based on their influence on the best site selection of fire stations in Erbil city. The factors considered included fire incident distance (FID), Primary Road Distances (PRD), Existing Fire Stations (EFS), Population Density (PD), industrial areas (IA), Hospitals and Health Centers (HHC), Parks and Playgrounds (PPG), Educational Institutions (EI), Polics Stations (PS), fuel stations (FS), Multi-Story Buildings and Apartments (MBA), Commercial Areas (CA), Built-up Areas (BUA), and slope (SL). Table 2 lists the criteria selected used in some of the papers. These fourteen parameters can be defined as the key factors that affect the suitability map for the most appropriate locations for setting up new fire stations Figure 3 illustrates the Euclidean Distance classified for each criterion used in the AHP method.

2.3.1 Fire Incidents Distance (FID)

In 2024, Erbil experienced a dramatic rise in the number of fire events, and according to the data provided by the Civil Defense Directorate, 1918 cases of residential, commercial, and vehicle fires resulted in 20 deaths, 74 injuries, and major material loss, with the heaviest impacts occurring in crowded areas, including Qaisary Bazar and Langa Bazar, where 185 shops were ruined. With this hazard in mind, the proximity of locations to previous fire incidents was identified as a key factor in vulnerability. Utilizing ArcMap 10.8.2, the location data of every fire incident were converted into latitude and longitude maps in ArcMap [2]. Euclidean distances from the locations to the historical fire occurrences were calculated. The importance of the distance to historical fire sites was proposed in the AHP model with a 13.37% weight, reflecting its critical role in emergency planning. Sites closer to previous fire hotspots were prioritized and ranked as one of five classes, as they represent areas were rapid response could save lives and reduce damage.

2.3.2 Primary Road Distances (PRD)

Another crucial factor in fire response operations is road accessibility [20]. The speed of any emergency response significantly increases when fire stations are close to major roads. The 60, 100, and 120-meter roads connect Erbil City's main residential, commercial, and industrial areas. The roads are designed to handle heavy traffic; however, because of the heavy volume of vehicles, access can occasionally be prevented during peak hours. In this study, the Euclidean distance between major roads and possible fire station locations was calculated using ArcMap 10.8.2. In the AHP process, sites close to these roads were prioritized and assigned an 11% weight. The existing fire stations along the sides of major roads, it is possible to respond to critical areas, such as industrial and densely populated areas, more quickly.

2.3.3 Existing Fire Stations (EFS)

Proximity to existing fire stations is an important consideration when choosing sites for new fire stations in a city to identify underserved areas and strategically place new stations where coverage is lacking [1, 21]. The design of the new fire stations in this study took into account those that already existed, as Erbil City has 11 fire stations in the city center, with additional stations in the wider Erbil Governorate inside the study area. figure 1 shows the fire stations currently exist and theirs coverages according to standards 4 kms as a buffer zone are considered to be 5 mins for arriving ambulance to disaster places.[22] indicated that with the Fire Department's assistance, a 4 km straight-line distance is the coverage standard. The distance to existing stations was assessed using the Euclidean distance, with closer proximity indicating a lower need for new stations [9]. Existing fire stations do not always eliminate the need for new stations, particularly in high-risk expanding areas. The AHP analysis gave this criterion a weight of 12%, emphasizing its function in enhancing coverage in high-risk areas and optimizing station distribution.

2.3.4 Industrial Areas (IA)

Because industrial areas are prone to great fire dangers, the site selection of fire stations is largely a result of this. The over-concentration of combustible materials, basic industrial equipment, and significant processes increase the fire danger of these industrial zones. The northern and southern industrial zones of Erbil are vital for the city’s economy, but contribute to the city’s increased fire risk.

In addition, some warehouses in these zones serve as urban infrastructure maintenance and supply transportation distribution; therefore, they need to be close to these warehouses to maintain supplies and distribution during emergency responses [23]. Coverage by existing fire service stations is quite good, but still requires improvement in urban planning. The Euclidean distance to industrial sectors was identified in ArcMap and input into the AHP model with a weighting of 4.97 %. In so doing, planners ensure that even well-covered areas serve as a cause for quick and assured fire response.

2.3.5 Hospitals and Health Centers (HHC)

This criterion was selected because of the significance of these facilities and the potential amount of property damage to people in the event of a fire [13]. [24] assigned 30% of the weights (percentages) to the distance to hospitals as an important factor in selecting fire station locations because quick access to medical facilities during fire emergencies is critical [23]. It is quite satisfactory in Erbil City, where inhabitants live close to healthcare centers in crowded urban zones, when fire outbreaks overlap with medical crises. In this study, we calculated the Euclidean distance to hospitals and health centers and allocated higher suitability scores to locations with shorter distances. The 7.98% weight according to the AHP model on this criterion is reflected in its critical contribution towards making emergency services efficient for a quick response to fires as well as medical emergencies.

2.3.6 Parks and Playgrounds (PPG)

The location of parks and playgrounds is another determinant of fire station site establishment, because these areas might have public meeting spots such as cafes, trees, and grass. Erbil City has many parks and rest areas that are close to cafés and heavily wooded, which makes them vulnerable to fire, especially during holidays and rest times [13, 23] When fire stations are placed near a park, they can manage quick intervention in case of an emergency. Therefore, in this study, the distance to parks and playgrounds were measure, and greater proximity to these areas was prioritized. The AHP process assigned a weight value of 7.12% to the Parks and Playgrounds criterion.

2.3.7 Educational Institutions (EI)

Closeness to learning establishments such as schools, colleges, and kindergartens is also very important for fire station placement in densely populated cities, as fire stations positioned close to educational establishments can significantly reduce emergency response time and possible damage [21]. The Euclidean distance to these institutions was determined, and preferences were assigned to points closer to schools and colleges. This measure corresponded to 5.61% weight in AHP, as this factor is important in improving the added value to public buildings that experience high foot traffic with regard to enhancing safety and accessibility.

2.3.8 Police Stations (PS)

The availability of police stations is a major consideration for determining the locations of fire stations owing to the need for cooperation of fire services during emergencies [21]. In Erbil City, the locations of police stations closer to possible fire station sites improve the general efficiency of emergency response. Using the Euclidean distance between fire station sites and the distance to the nearest police stations, the AHP method gave a weight of 5.61%, which is a good measure of its importance in the smooth and timely cooperation of fire and law enforcement during critical events.

2.3.9 Fuel Stations (FS)

Fuel facilities are very hazardous, and proximity to fuel stations is a major criterion in selecting fire station locations. Fuel stations are full of highly flammable materials; therefore, they are hot spots that must respond quickly to emergencies. In Erbil City, the way fuel stations are distributed within the population and commercial zones make their location next to fire stations even more important. Future work shows the need to include fuel station locations in urban risk evaluation and emergency planning because of their impact on fire propagation and public safety [25, 26]. Estimates of Euclidean distance to fuel stations were made to identify zones with increased fire service coverage requirements. In the AHP analysis, a weight of 6.51% was considered, which stressed the importance of decreasing the response time for potential fire danger threats and protecting high-hazard urban areas.

2.3.10 Multi-Story Buildings and Apartments (MBA)

Multistory buildings and apartments are fundamental selection criteria for fire station sites because such constructions pose unique challenges in the case of fire emergencies. Evacuation and firefighting in high buildings are usually difficult because of complications such as vertical access, smoke diffusion, and occupant behavior during emergencies [27, 28]. In Erbil city, high-rise buildings and apartment blocks pose a higher fire risk owing to their high density level. Fire stations around these areas provide faster responses, reduced possibility of large-scale damage, and access to rescued people trapped on higher floors [29]. The Euclidean distance to these buildings was determined to select areas that required more intense emergency services. This criterion was allocated 5.82% weight in the AHP analysis.

2.3.11 Commercial Areas (CA)

Fire station locations close to business areas are an important factor during site selection because these areas often have high human and business activities, which can cause fires. Commercial centers such as shopping malls, restaurants, and markets play a very important role in this city, but also face fire hazards because of overcrowded spaces. Fire stations within the reach of such districts guarantee a quick-fire response, and hence prompt minimization in terms of property losses and casualties. Calculations of the Euclidean distance to commercial areas where closer sites had a higher strategic value of 5.82% in the AHP analysis indicated its contribution to mitigating fire hazards in high-density commercial spaces. A step in the same direction was taken by [30], who adopted commercial centers as an important criterion in their GIS-based MCDA model for deciding the placement of civil defense centers in Al-Riyadh City.

2.3.12 Population Density (PD)

Population density is the most applied and influential criterion for fire station and emergency facility planning in various geographic and methodological areas. For instance, [31] used a hybrid FUCOM-COCOSO model in Misurata, Libya, and attached maximum significance (weight = 0.348) to the population density in their siting analysis. Analogously, population density was also a key input in the DEMATEL-based MCDM model of urban fire and emergency services proposed by [32], which is highly important in planning effective emergency response infrastructure.

In Erbil City, the density of urban neighborhoods reached a population figure of 116,942 people in 2022 [19]. To accommodate population growth, a growth rate of 2.16% was applied to 2023 and 2024 to provide growth in population estimates [33] equation1. The locations of fire stations identify areas of great population as places of priority, where a large number of buildings, businesses, and people reside, which will automatically attract more fire incidents. The Euclidean distance to high-density areas were modelled, and the closer to high-density zones, the higher the suitability score. This criterion received a weighting factor of 6.4% in the AHP analysis, which reflects its significance in establishing ideal fire station locations so that those structures are in positions where they have the maximum reach to serve the population.

$$P_t = P\text{\^{}}0 \times (1 + r)^{t} \quad (1)$$

where:

P_t = projected population in year t

P_0 = base year population (e.g., population in 2022)

r = annual growth rate (as a decimal; 2.16% = 0.0216)

t = number of years from the base year (e.g., for 2023, t = 1) [34]

2.3.13 Built-up Areas (BUA)

Built-Up Areas (BUA), which include hotels, motels, and hostels, are central when selecting a fire station site because of their high population density and increased risk of fire. Fire stations must be close to the BUA to speed up response times, particularly in crowded areas. To overcome this, the Euclidean distances to these facilities were computed, and the preferred sites were closer to the built-up areas. This criterion received a weight of 5.61% in the AHP analysis, reflecting its importance in increasing safety and accessibility in densely populated cities [1] confirmed this strategy; their research in Wuhan showed that operationally locating fire stations utilizing population density and built-up regionality greatly improved emergency response capacity.

2.3.14 Slope (SL)

Fire station site selection has slope as a critical factor, considering its influence on the accessibility of fire services and response times in regions with difficult topography. In steeper terrains, emergency vehicles may be required to slow down response processes [21] In Erbil City, where areas have low slopes and are better reachable because of their plain surface geography, which is good for fire stations. The slope was calculated using a Digital Elevation Model (DEM) and classified into five categories, with lower slopes ranked as the most suitable for fire station locations. The weight of this criterion was assigned as 3.66% through AHP pairwise comparison, reflecting the importance of terrain in determining effective fire station accessibility.

Table 2: Summary of literature review highlighting the application of fire station site selection criteria in recent studies.

Reference	FID	PRD	EFS	IA	HHC	PPG	EI	PS	FS	MBA	CA	PD	BUA	SL
[35]			✓		□		□				□			
[36]		□								□		□	□	
[10]		□			□		□					□		
[37]		□									□	□	□	
[38]		□	□						□			□		
[39]		□			□							□		□
[40]			□		□		□	□	□		□			
[32]		□	□	□					□			□	□	
[41]	□	□	□		□		□							
[42]		□										□		□
[43]		□				□						□	□	
[21]		□	□		□			□				□	□	□
[44]														
[13]		□	□		□	□					□	□		
[45]	□	□	□		□			□				□		

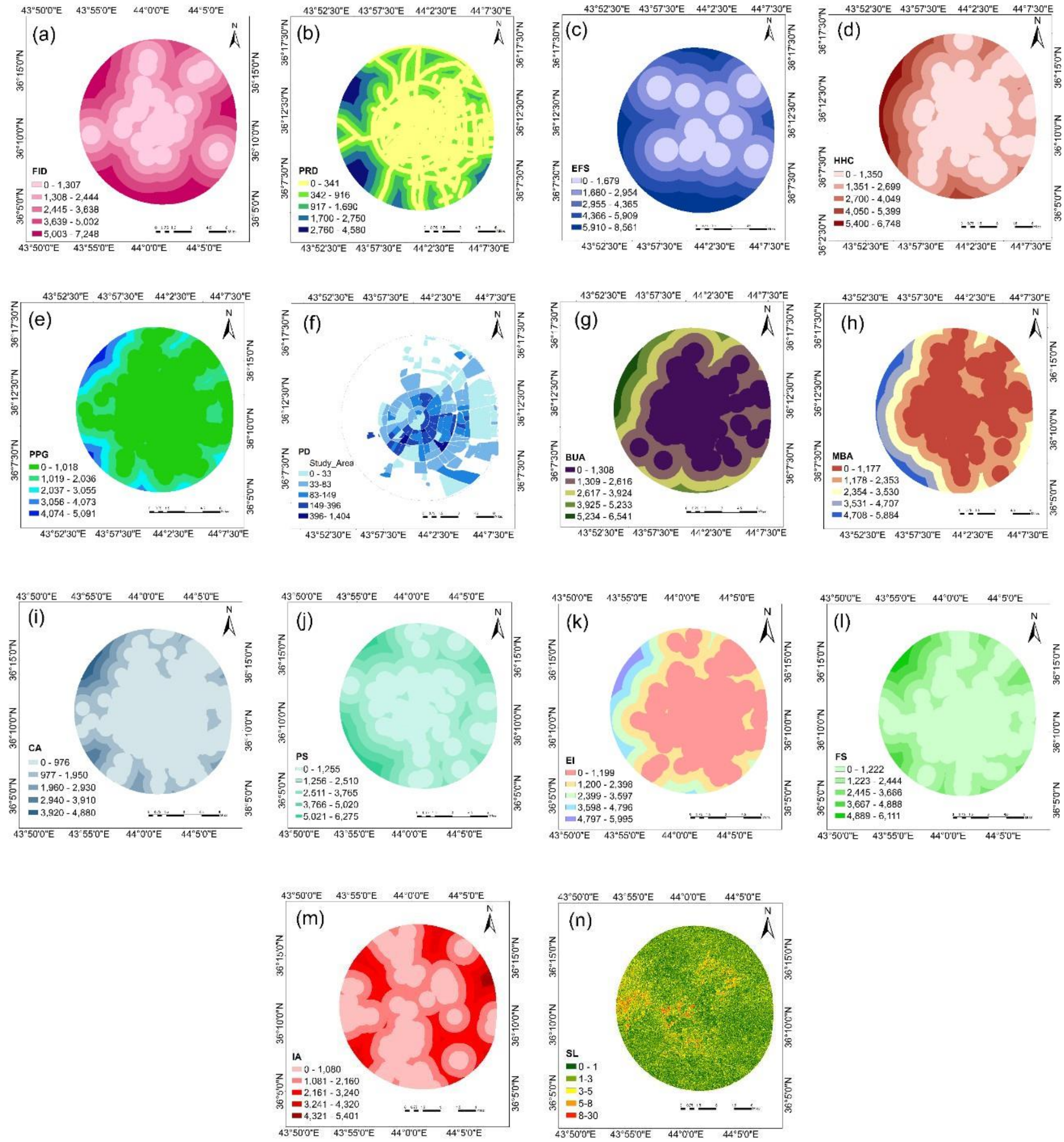

Figure 3: The Contributed Factors for Optimum Fire Station Mapping, Including: (a) FID, (b) PRD, (c) EFS, (d) HHC (e) PPG, (f) PD, (g) BUA, (h) MBA, (i)CA, (j) PS, (k) EI, (l) FS, (m) IA, and (n) SL.

2.4 Fire station maps using AHP technique

2.4.1 Geographic Information System (GIS)

GIS is a computer tool that asks insightful queries, analyzes and combines information in the fields of land management, emergency management, environmental management, sciences, and public health. The results were represented as a cluster of data to see multiple features on a map. GIS aids in the collection and display of data and depends on the analysis of spatial data, for example, monitoring and evaluation factors that could affect it, creating ways to control it, and including humans; the data are presented in layers, and it can easily be accessed or queried [45]. A GIS tool is required to rank alternative positions for the stations and estimate their performance. Currently, GIS is the main application used to select a site. There is no doubt that site selection is a key factor, as it would be very difficult and costly to make another choice. Making an imprecise choice might increase transportation costs and cause the loss of qualified labor [41].

2.4.2 Multi-Criteria Decision Analysis (MCDA)

MCDA plays a key role in emergency preparation for cities, allowing decision-makers to consider various situations with several different requirements. MCDA consists of many methods, but with the AHP method, MCDA, making a decision becomes easier as you first organize the problem, then assess each criterion based on others and finally rate the alternatives' importance [46].

Recent studies have proven that using AHP helps to make the system of urban emergency shelters more efficient [47]. [48] approached the subject by introducing a hierarchical fuzzy MCDA model in 2024 to identify urban zones that must deal with a number of risks. [49] prove that AHP can be included in MCDA to help improve how cities manage with risks and prepare for emergencies

2.4.3 Analytic Hierarchy Process (AHP)

For complex decision problems, AHP uses a simple form of MCDA to select the best option by allowing comparisons of all steps in a hierarchical structure [50]. The study used GIS and AHP by assigning weights to the map layers and then combining them with the attribute map layers. The main steps for implementing the AHP model are as follows.

Step 1: Breaking down a complicated, unstructured problem into criteria, alternatives, and decision goals.

Step 2: Create an AHP hierarchy model that is applied to the suitability map for choosing urban emergency facilities.

Step 3: Create a judgment matrix that reflects the subjective preferences of experts for criteria and alternatives by employing the pairwise comparison method.

Equation (2) illustrates that the results of the comparisons are an appositive pairwise comparison matrix A=aij, with reciprocal elements for all aji=1/aij.

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \quad (2)$$

(i, j = 1, 2, ..., n)

Step 4: Determine the relative weights of each criterion and assign ranking values of relative importance to the subjective judgments using the 9-point ratio scale proposed by Saaty [9].

Step 5: Using the consistency ratio (CR), we verify that the pairwise comparison evaluations are consistent. When DMs specify their individual criteria preferences, consistency guarantees coherence in their judgments. The consistency level was acceptable, and the comparison judgments were considered trustworthy if the CR was less than 0.1.

Step 6: Combine the ratings for each criterion and the alternatives, and then use them to calculate how much each alternative priority is weighted by each criterion [38].

$$CR = \frac{CI}{RI} \quad (3)$$

Where:

CR= Consistency Ratio

CI= consistency Index

RI= is Random Inconsistency has already been provided by SAATY,

If CR ≤ 0.1, it is acceptable; if CR > 0.1, it is not acceptable [51].

The PC matrix of the literature and experts' opinions were used to assess and arrange the impacting factors in ranking order. The suitability areas for new fire stations in Erbil City were determined byintegrating 14 critical criteria using the AHP technique. AHP is acknowledged in Multi-Criteria Decision-Making (MCDM) for urban planning and emergency analysis, mainly when dealing with complex reasons. Using this technique, officials can evaluate several factors and accurately identify the best stations for fire services [52].

AHP can simplify tough decisions by dividing them into stages and calculating the relative rank of each factor [53, 54]. With the PC matrix, each of the factors that affected showing fire stations in areas was assigned a weight connected to accessibility and safety.

The weights were established in ArcMap 10.8.2, and the process of the methodology used in this study is shown in Figure 4. both the weights assigned to the factors and the rankings for each class of criteria in Tables 3 and 4. To check the reliability of the comparisons, the CR was computed, and the result was less than 10%. The results showed an acceptable value of 3.1%; therefore, the consistency was considered acceptable. This proves that the decision to assign weights works well and that the approach and results are reliable [55].

Table 3: AHP weight comparison matrix

Factors	FID	PRD	EFS	HHC	PPG	PD	BUA	MBA	CA	PS	EI	FS	IA	SL	W(%)
FID	1	2	3	2	2	2	2	2	2	2	2	3	3	3	13.37
PRD		1	2	2	1	2	2	2	2	2	2	2	3	2	11
EFS			1	2	1	3	1	2	2	2	2	3	5	3	12
HHC				1	1	2	1	1	1	1	2	1	3	3	7.98
PPG					1	1	1	1	1	2	1	2	1	2	7.12
PD						1	1	1	1	1	1	1	3	2	6.4
BUA							1	1	1	1	1	1	1	1	5.61
MBA								1	1	1	1	1	1	2	5.82
CA									1	1	1	1	1	2	5.82
PS										1	1	2	1	1	5.61
EI											1	1	1	2	5.61
FS												1	0.5	2	5.03
IA													1	1	4.97
SL														1	3.66
Sum of Weights (%)															100.00

Table 4: The rankings and weights of each 14 parameters used in FSM (W: weight; R: ranking)

Factors	Classes	W (%)	R	Factors	Classes	W (%)	R
Fire Incidents Distance	0 - 1,307	13.37	1	Multi-Story Buildings and Apartments	0 - 1,177	5.82	1
	1,308 - 2,444		2		1,178 - 2,353		2
	2,445 - 3,638		3		2,354 - 3,530		3
	3,639 - 5,002		4		3,531 - 4,707		4
	5,003 - 7,248		5		4,708 - 5,884		5
Primary Road Distances	0 - 341	11	1	Commercial Areas	0 - 976	5.82	1
	342 - 916		2		977 - 1,950		2
	917 - 1,690		3		1,960 - 2,930		3
	1,700 - 2,750		4		2,940 - 3,910		4
	2,760 - 4,580		5		3,920 - 4,880		5
Existing Fire Stations	0 - 1,679	12	5	Police Stations	0 - 1,255	5.61	1
	1,680 - 2,954		4		1,256 - 2,510		2
	2,955 - 4,365		3		2,511 - 3,765		3
	4,366 - 5,909		2		3,766 - 5,020		4
	5,910 - 8,561		1		5,021 - 6,275		5
Hospitals and Health Centers	0 - 1,350	7.98	1	Educational Institutions	0 - 1,199	5.61	1
	1,351 - 2,699		2		1,200 - 2,398		2
	2,700 - 4,049		3		2,399 - 3,597		3
	4,050 - 5,399		4		3,598 - 4,796		4
	5,400 - 6,748		5		4,797 - 5,995		5
Parks and Playgrounds	0 - 1,018	7.12	1	Fuel Stations	0 - 1,222	5.03	1
	1,019 - 2,036		2		1,223 - 2,444		2
	2,037 - 3,055		3		2,445 - 3,666		3
	3,056 - 4,073		4		3,667 - 4,888		4
	4,074 - 5,091		5		4,889 - 6,111		5
Population Density	0-33	6.4	5	Industrial Areas	0 - 1,080	4.97	1
	33-83		4		1,081 - 2,160		2
	83-149		3		2,161 - 3,240		3
	149-397		2		3,241 - 4,320		4
	397-1404		1		4,321 - 5,401		5
Built-up Areas	0 - 1,308	5.61	1	Slope	0-1.3	3.66	5
	1,309 - 2,616		2		1.3-3		4
	2,617 - 3,924		3		3-5		3
	3,925 - 5,233		4		5-8		2
	5,234 - 6,541		5		8-30		1

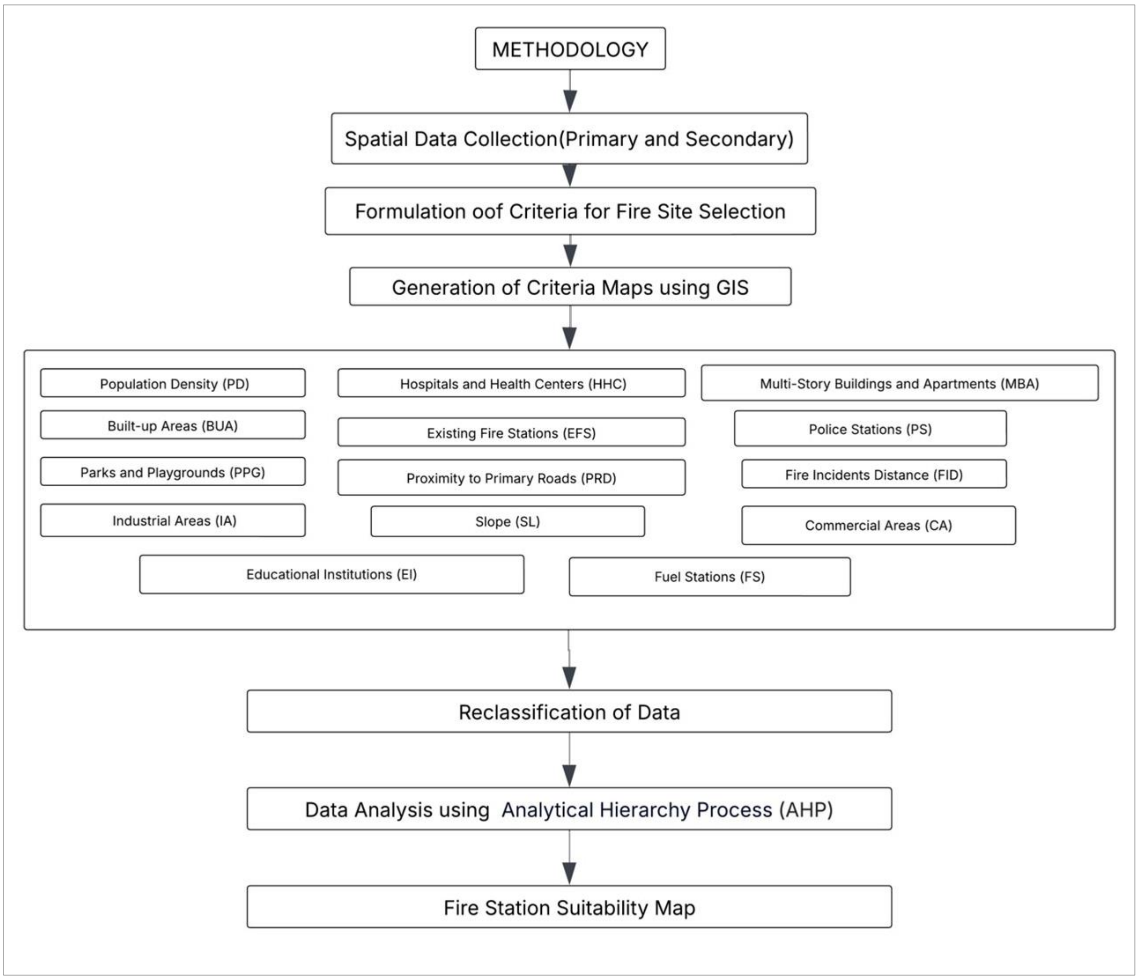

Figure 4: methodology flow chart

3. Results and Discussions

3.1 Fire Station Suitability Mapping

Using the GIS-AHP methodology, fire station suitability across Erbil City was analyzed and categorized into five suitability classes ranging from 1 (Very Low) to 5 (Very High). The final suitability map Figure 5A illustrates the spatial distribution of these classes, with higher suitability zones generally concentrated in the central-eastern parts of the city, while lower suitability areas appear more on the outskirts.

The total area of the study region is approximately 383.60 km², of which 186.35 km² is classified as urban. Although existing fire stations are distributed throughout the city, they do not adequately cover the entire area.

According to standard fire service guidelines [56] and as illustrated in Figure 1, a fire station with a 4 km service radius, assuming an emergency vehicle speed of 40–50 km/h, can typically cover an area of approximately 295 km². However, consultations with the Erbil Civil Defense Department revealed that these standards are difficult to apply locally because of the absence of dedicated service roads for emergency vehicles, high vehicle density, and frequent traffic congestion during the peak hours.

To better reflect the real-world conditions in Erbil, two alternative coverage scenarios were developed. The first assumes a 3 km radius, covering approximately 216 km², while the second scenario applies a 2.5 km radius, covering approximately 174 km².These adjusted buffers provide a more realistic estimation of effective service areas under the city's current transportation and infrastructure constraints.

The suitability results were reclassified into zonation levels to better support planning and decision making Figure 5B. The spatial overlay indicates that zones 4 and 5—corresponding to “High” and “Very High” suitability—represent the most critical areas needing improved emergency response infrastructure. The majority of these zones are seen in Municipalities 3, 4, and 5, and Municipality 6 has a modest chance of further growth.

As seen in Table 5, the highest proportion of land (29.4%) is in the “Low” suitability class, followed by “Very Low” (24.9%). Only 8.3% of the total area of Erbil (within the 150 m service buffer) falls into the ‘Very High’ suitability category emphasizing that there are relatively few spots were fire stations would perform best.

Table 5: Fire station suitability classes by area and percentage coverage.

Fire Station Suitability Class	Area (km²)	Percentage (%)	Priority
1 – Very Low	45.89	24.89	Low
2 – Low	54.23	29.42	Low
3 – Moderate	39.69	21.53	Medium
4 – High	29.13	15.80	High (needs service)
5 – Very High	15.40	8.35	Very High (critical)

Dense buildings, activities from factories, and a history of many fires usually identify high-priority zones (Classes 4 and 5). As an example, regions near Langa Bazar, where many fires have occurred, are placed in the “Very High” suitability zone.

The municipalities with the highest risk in Areas 3, 4, and 5 should be addressed immediately, which is 45.68% of the total area of the study. The expansion of a city means that these municipalities should be monitored carefully for effective planning.

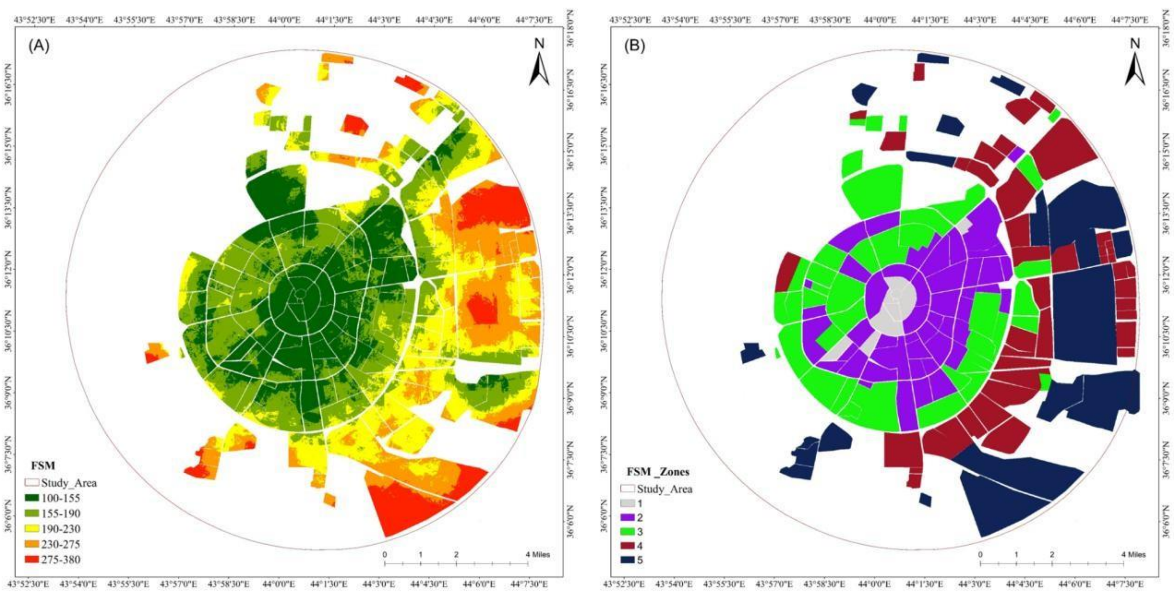

Figure 5 A: Final Fire Station Suitability Map, B: Zonation Map Based on Suitability Levels

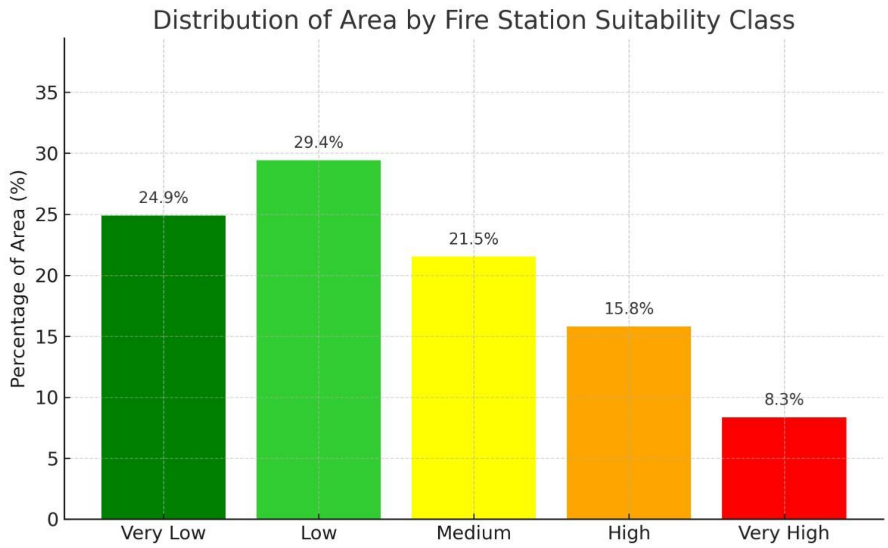

Figure 6: Bar Chart of Suitability Class Distribution

3.2 Validation of the AHP Suitability Model

To validate the model, a Receiver Operating Characteristic (ROC) curve was generated using Scikit-learn, a Python machine learning library that provides tools to train models, evaluate them, and plot things like the ROC curve. Considering the existing fire station locations (positive class) and random background points (negative class), the area has no existing fire stations considered as a negative class. The suitability values were extracted from the FSM raster. The Area Under the Curve (AUC) achieved was 0.910, indicating excellent model accuracy Figure 7. The red curve demonstrates the high predictive power of the model in differentiating suitable locations from unsuitable locations for fire station placement. An AUC of 0.910 was considered outstanding, confirming a strong alignment between the predicted suitability and actual ground-truth data. [57, 58] used the Receiver Operating Characteristic (ROC) curve and the Area Under the Curve (AUC) to validate forest fire susceptibility maps, indicating that the result of AUC has revealed results.

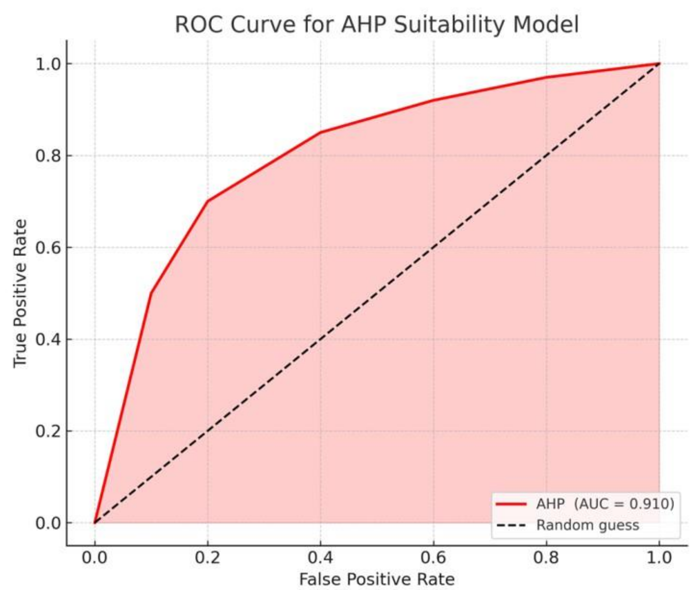

Figure 7: ROC Curve for Model Validation

In the 3rd edition of "Applied Logistic Regression" by [59] provides guidelines for interpreting AUC (Area Under the Curve) values, a measure of a model's predictive accuracy which indicates that from 0.9–1.0 = outstanding, 0.8–0.9 = excellent, 0.7–0.8 = acceptable and <0.7 = poor. This validation reinforces the robustness of the selected criteria and confirms the effectiveness of the AHP-based MCDA approach in emergency planning [60].

3.3 Summary and Strategic Implications

The integration of spatial analysis and expert-based weighting produces a reliable model for fire station site selection. Furthermore, the low AHP consistency ratio (CR = 3.1%) confirms the reliability of expert judgments in pairwise comparisons [61]. The results offer a practical, evidence-based framework for fire station expansion in Erbil, which supports both current risk reduction and future urban resilience planning.

Overall, these results offer important insights to planners and local authorities. Placing fire stations in at-risk areas and preparing for future city growth helps Erbil to develop a stronger emergency response network.

4. Conclusions

This study developed a practical and dependable method for identifying the most suitable locations for new fire stations in Erbil City by integrating Geographic Information Systems (GIS) with Analytic Hierarchy Process (AHP). By combining comprehensive spatial data with informed expert judgment, the research identified the eastern and southern parts of the city, particularly Municipalities 3, 4, and 5, as areas in critical need of improved emergency response coverage.

Municipality 4 rose to the top because it was under a serious threat and had very high urban activity. Even though moderate suitability makes it uncertain, municipality 6 should be carefully watched as the city continues to develop. Its unique feature is the combination of tough technical principles and relevance to real life. The model shows that it can accurately and reliably support planning with an accuracy of 0.910. Importantly, this method is not limited to Erbil; it offers a flexible framework that other rapidly urbanizing cities can adopt to strengthen their emergency infrastructure.

When spatial analysis is integrated into strategic planning, this research gives decision-makers the resources to make better choices regarding resource allocation. This study leads to making cities safer by putting fire stations where they are needed by the residents, not just on maps.

Conflict of Interest

The authors have no conflicts of interest to declare

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