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Spatial Optimization of Urban Fire Stations Based on the SAVEE Model

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Abstract: Fire emergency service is an important part of urban public health and safety system,and the rationality of its layout directly affects the efficiency of disaster relief response. In this paper, the central urban area of Kunming City is selected as the study area, based on POI, road network and other geospatial data, through AHP hierarchical analysis method and SAVEE model, to realize the identification of potential fire risk area and suitable area for fire stations siting in the study area, and to use the model for minimizing the Number of facilities for spatial optimization of fire station siting. The results show that: 1) the fire risk assessment system is applicable to the study area, and the fire risk is mainly distributed in the northwestern part of the study area; 2) the layout of the existing fire stations is limited, and the existing coverage rate reaches only 71.47%; 3) 6 new fire station sites are added, and the coverage rate increases by 19.75%, and the total coverage rate reaches 91.22%, and the optimized indexes have been greatly improved.

Keywords: Fire station; SAVEE model; optimal site selection; spatial pattern visualization.

1. Introduction

Urban development cannot be separated from the cornerstone of safety, the optimization of the layout of the city fire station is to improve the city's rescue capacity, to protect the effective means of urban safety. In recent years, the city scale gradually expanding, fire risk factors are more complex, many urban infrastructure construction and urban development is not synchronized with the problem is increasingly prominent, mainly manifested as follows: the urban population with the process of urbanization continues to gather, the emergence of a "multi-purpose" places, large commercial complexes, old districts and other personnel intensive, complex structures Such places are prone to safety hazards, and the sharp increase in high-rise buildings and underground buildings makes fire prevention and control and fire rescue more difficult[1] . The layout of the fire station is an important part of urban fire planning, and whether the layout of the fire station is reasonable or not is directly related to the effect of fire fighting after a fire in the future. Therefore, the research on fire station sites is still an important topic in the field of disaster science at present.

The insufficient number of urban fire stations makes the service range of a single fire station wide. In recent years, scholars at home and abroad have carried out research on fire station planning using spatial optimization models or related algorithms. Bai Hua et al. explored the optimization of fire station layout planning based on the "location-allocation" model, and verified the research through the accessibility model[2] ; Wu Meiwen et al. optimized the fire station layout based on the discrete positioning model[3] ; Zeng Liqun et al. applied the Dijkstra shortest path labeling method, and took the minimum point of the path sum as the new fire station point[4] ; Hu Chuanping et al. optimized the fire station layout through the setcovering, maximum coverage, and maximum coverage algorithms[5] ; Zhu Mingming et al. use hierarchical analysis to spatially assess the existing fire fighting facilities and spatially optimize the layout[6] ; Liu Shang et al. based on spatial syntax and GIS network analysis method, from the fire station to the new fire station, the new fire station will be built by using the Dijkstra shortest path labeling method. analysis method, from the fire station site selection, layout and responsibility area delineation and other aspects of the systematic study of the optimization of fire station layout[7] ; Yu Zhijin et al. proposed the model intersection method, aiming at optimizing the spatial layout of the fire station[8] ; Chen Kaijia et al. based on the particle swarm algorithm, the spatial layout mode of the fire station was studied[9] ; Guo Jingwen et al. based on [10]Lu Houqing et al. explored the optimization of urban fire station layout based on continuous coverage[11] ; Hou Guanjie considered the fire spreading pattern and multiple fire risks with the help of a non-dominated sorting genetic algorithm (NSGA-II) with elite strategies[12] .

Based on the above research, this paper tries to solve the following problems in the optimization of urban fire station siting: 1) Compared with the use of blocks to simulate the fire occurrence points, POI point data provide more accurate data support for the study of fire station siting, identify the spatial distribution of fire risk more accurately, and thus more accurately assess the fire risk of different locations; 2) Comprehensively take into account the degree of sensitivity of different cities to various types of fire risk factors and Comprehensively consider the sensitivity of different cities to various fire risk factors and the influencing factors of fire station siting, so as to make the siting of fire stations more precise and targeted; (3) Fully consider the economic requirements of fire station construction in different cities, and assess the potential impact of existing fire stations on the construction of new stations, so as to ensure the optimal allocation of resources.

This paper takes residents as the main body and the central urban area of Kunming City as the research object, relying on ArcGIS software, based on data such as point of interest (POI) and topography, and utilizes AHP hierarchical analysis and SAVEE model to assess the fire risk factors. The coverage area of fire stations and the coverage amount of fire demand points are taken as the construction indexes, and the location ensemble coverage model is used to plan the layout of fire stations, so as to solve the problems of uneven distribution of fire station points and too large responsibility area.

2. Research Ideas, Methods

2.1. Research ideas

1) Spatial identification of potential fire risk areas and suitable areas for fire station siting. Classify different influencing factors and get the weights of each factor through AHP hierarchical analysis; calculate the density distribution of each factor according to the spatial distribution of fire potential risk areas, environmental factors and socio-economic factors; based on the SAVEE model, standardize the results of the density analysis and put the weights on the results, and then substitute them into the iterative equations to identify the spatial distribution of the fire potential risk areas and the suitable areas for siting of the fire stations. Generate fire station candidate points.

2) Optimized layout of fire stations. Establish a road network model to provide a solid foundation for subsequent analysis. Analyze the coverage status of the existing fire stations, and apply the location ensemble coverage model for spatial optimization of fire station locations in areas lacking fire station coverage.

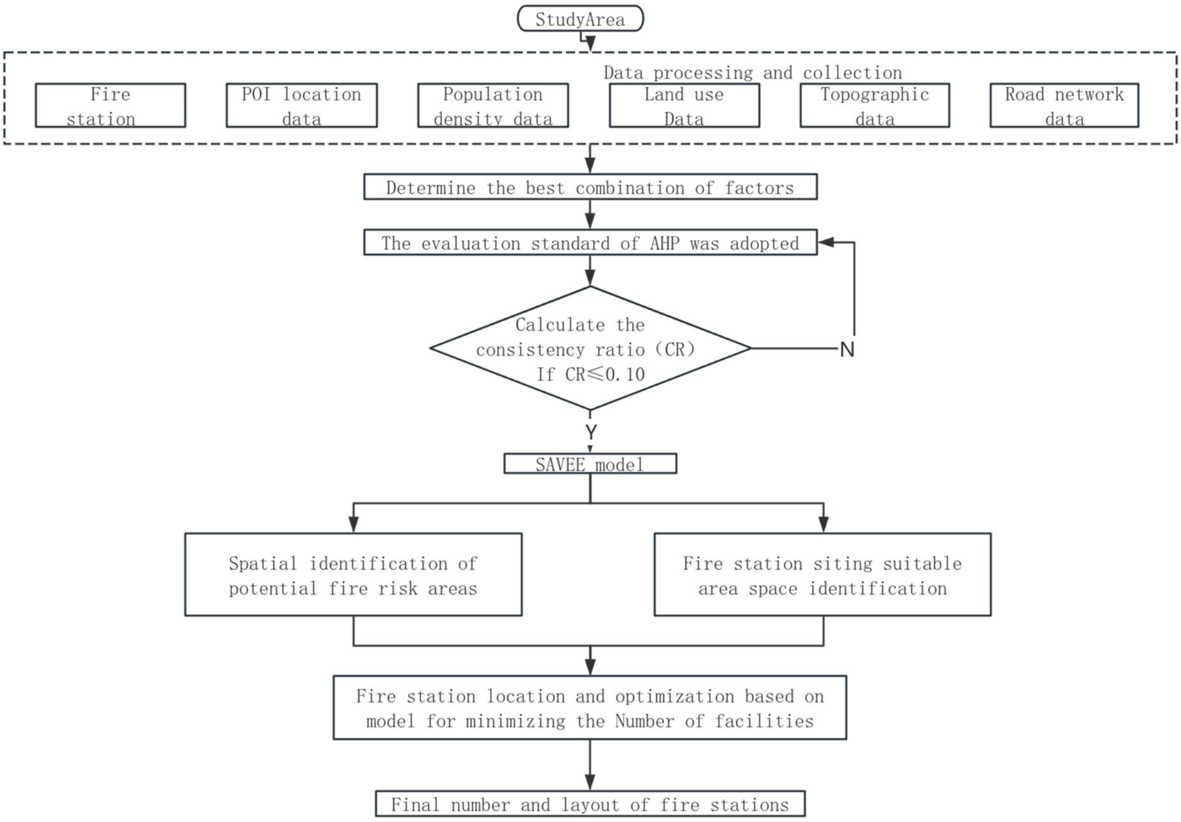

Figure 1. Research Process for Spatial Optimization of Fire Station Location in Cities

2.2. Research methodology

2.2.1. SAVEE model

SAVEE (special appraisal and valuation of environment and ecosystems), an integrated methodology for spatial valuation developed by the STARR Laboratory at Texas A&M University for the quantitative treatment of complex decision-making and valuation problems[13] . In this paper, the data are analyzed and integrated with the help of GIS to produce quantitative and visualized evaluation results. The main steps of this paper to achieve fire risk quantification using this method include (1) factor selection and quantification, (2) numerical normalization, and (3) iterative operations.

The SAVEE model provides different standardized equations for quantifying the spatial heterogeneity of fire risk and improves the shortcomings of traditional weighted evaluation methods. All risk factors are converted into values defined between (-1,1) by standardized equations to achieve uniformity in the evaluation of spatial values of factors. Among them, the value of the influence factor in (-1,0) is a negative factor, which plays a negative role in evaluating the factor, and the standardized equations are (1)~(2); the value of the influence factor in [0,1) is a positive factor, which plays a positive role in evaluating the factor, and the standardized equations are (3)~(4).

$$V = -\left(e^{\frac{-(x+1)}{|A|}}\right)^{5}, \ V \propto X \tag{1}$$

$$V = \left(e^{\frac{-(x+1)}{|A|}}\right)^{5} - 1, \ V \propto 1/X \tag{2}$$

$$V = 1 - \left(e^{\frac{-(x+1)}{|A|}}\right)^{5}, \ V \propto X \tag{3}$$

$$V = \left(e^{\frac{-(x+1)}{|A|}}\right)^{5}, \ V \propto 1/X \tag{4}$$

In equations (1) to (4): V is the standardized value; x is the independent variable, A is the critical value of x. $V \propto X$

indicates that the independent variable is positively correlated with the amount of value, and$V \propto 1/\ X$ indicates that the independent variable is negatively correlated with the amount of value.

After deriving the standardized values of the different factors, together with the weights derived from the AHP hierarchical analysis method, the two-by-two iterative operation was performed on the values of all the factors using the iterative equations (5) to (7), as shown in Figure 2.

$$I_{(A)}>0, I_{(B)}>0 \ when I_{AB} = I_A + I_B - I_A I_B \tag{5}$$

$$I_{(A)}<0, I_{(B)}<0 \ when I_{AB} = I_A + I_B + I_A I_B \tag{6}$$

$$\text{In other cases,} I_{AB} = \frac{I_A+I_B}{1-min（|I_A|，|I_B|）} \tag{7}$$

In Eq. (5) to Eq. (7): I_A and I_B refer to the standardized values of factors *A* and *B*, which take the range of [-1,1], and I_{AB} is the standardized score of factors *A* and *B* iteratively.

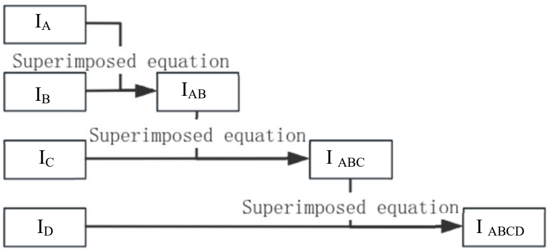

Figure 2. Flow of SAVEE iterative equation realization
Figure 2. Implementation Process of SAVEE Overlay Equation

2.2.2. Location set coverage model

The Location Aggregation Coverage Model is concerned with determining the minimum number of facility points to achieve economy in resource allocation while satisfying the premise that all demand points are covered by at least one facility point. The mathematical model is as follows:

Symbols are set: I is the set of demand points; J is the set of facility point candidates; dij is the distance between demand point i and facility candidate j; and Dc is the effective coverage distance of supply points.

Objective function:

$$\mathrm{minp} = \sum_{j=1}^{n} x_j \tag{12}$$

Constraints:

$$\sum_{j=1}^{n} y_j x_j \geq 1 \tag{13}$$

$$x_j \in (0,1); j = 1,2,\cdots,n \tag{14}$$

2.2.3. Layout constraints

Before the spatial optimization analysis of the fire station sites, the road network needs to be modeled. After determining the network connection rules and ensuring the topological correctness of the road data, ArcGIS is utilized to establish the network dataset. Fire trucks enjoy road priority when carrying out emergency tasks, and this characteristic is configured accurately and reasonably to ensure that the network analysis model can accurately reflect the actual access of fire trucks. According to Article 13 of Chapter 3 of the Urban Fire Station Construction Standards (Jianbiao 152-2017)[16] , taking into account the actual situation of different cities, the layout of the fire station is generally determined on the principle that the fire department arrives at the edge of the precinct within 5 minutes after receiving the order to go out. According to the data statistics of the "2023 Traffic Analysis Report of China's Major Cities" published by Gaode Map, the speed field is assigned a value, which is shown in Table 1.

Table 1. Road speed assignment for each level (km/h)
Table 1. Speed Assignments for Different Levels of Roads (km/h)

Type of road	Planning speed limit	High average speed	Average speed throughout the day	Research speed assignment
highway	≤100	51.35	77.84	60
trunk road	30-70	27.41	41.65	40
secondary road	≤50	23.09	37.43	30

3. Overview of the Study Area and Data Sources

3.1. Overview of the study area

Kunming City is the capital of Yunnan Province, the center city of the central Yunnan city cluster, and an important tourist, commercial and trade city in China. During the "13th Five-Year Plan" period, there were 31,867 fires in the province, with an average of 6,373 fires per year, and the average annual fire death rate of the province's population of 100,000 was 0.16, with an average annual fire loss rate of GDP of 0.057 per thousand. Kunming City, the government published 1 "Kunming" 14th Five-Year "Fire and Rescue Career Development Plan" proposed that by the end of 2025, Kunming City, the average annual fire mortality rate of 100,000 people in 0.18 or less, the average annual GDP fire loss rate of less than 0.06%. The average annual human-caused fire incidence rate is less than 0.55. Studying the spatial layout of fire stations in this area is of reference value for the development planning of fire and rescue undertakings in Kunming. In this paper, the boundary of the study area is selected based on the Ring Road in the urban area of Kunming, with a total area of 514.68km^2.

3.2. Data sources

The research data in this paper includes: 1) POI location data: originated from Baidu pickup coordinate system (https://api.map.baidu.com/), which converts buildings or regional places into geospatial points. It contains a total of 40,595 valid data through data cleaning, coordinate conversion and screening integration, with an average distribution density of 78/km^2.2) Road network data: pre-processing such as road network error checking and editing modification is carried out to get the road network data.3) Fire station point location data: point location data are obtained from Gaode map and Baidu map, and after data de-emphasis, merging and screening out the low-grade firefighting facilities, it A total of 20 fire station locations in the study area were obtained.4) Topographic data: obtained from NASA Earth Science Data website with a resolution of 12.5 m. Kunming City is located on the Yunnan-Guizhou Plateau, and the topography of the city shows an overall trend of high in the north and low in the south, with a gradual decrease from the north to the south and a stepped pattern.5) Population density data: obtained from the Worldpop platform, with a resolution of 100 m.6) Land use Data: Sourced from the Resource and Environment Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn), with a resolution of 10m.

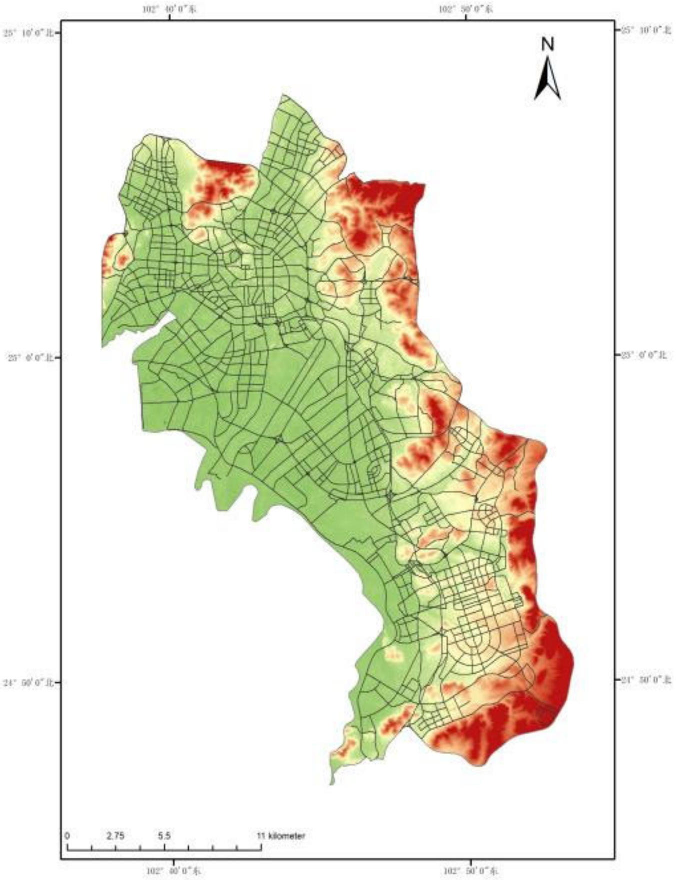

Figure 4. Overview of the Study Area

4. Spatial Identification of Potential Fire Risk Areas

4.1. POI-based fire risk assessment

Spatial identification of potential fire risk areas, the first step is to delineate the smallest spatial analysis unit. The traditional spatial identification unit, often neighborhoods, blocks as the minimum unit of demand points, with the rapid development of the economy and society, urban buildings from the ground to the expansion of the above ground and underground, "multi-combined" places continue to increase, the traditional spatial identification is not accurate enough to meet the needs of the reality of[17] . In GIS, POI refers to real geographic entities that can be abstracted into points, which present actual buildings or regional places in the form of geospatial points. Therefore, this paper adopts POI data as the associated element analysis.

In this paper, combining the Urban Fire Planning Code, the Fire Protection Law of the People's Republic of China (2019 Revision), and the Definition Standards for Key Units of Fire Safety in Yunnan Province (Trial), all types of POI data are categorized into six types of fire potential risk factors based on the degree of fire danger and disaster-bearing body bearing disaster. Each type of fire risk factor has a different degree of influence on fire risk, based on the current situation of the city and reference to previous literature, AHP hierarchical analysis is used to assess each type of fire risk factor, and its specific classification and weight are shown in Table 1~Table 2.

Table 2. Classification of Fire Risk Factors

Fire risk factors	POI type	impact factor	relevance
flammable and explosive	Gas stations, filling stations, chemical plants, etc.	positive factor	positive correlation
Vulnerable groups	Schools, general hospitals, etc.	positive factor	positive correlation
Public Gathering Category	Shopping malls, hotels, stadiums, hotels, train stations, etc.	positive factor	positive correlation
class under enhanced protection	Government agencies, scenic spots, libraries, science and technology centers, archives, art galleries, museums, etc.	positive factor	positive correlation
Labor-intensive	Large factories, large companies, etc.	positive factor	positive correlation
General risk category	Residential area, office building, etc.	positive factor	positive correlation

Table 3. Weights of Risk Zones

risk area	weighting	CR value
flammable and explosive	0.218	0.010
the economically and politically marginalized	0.162	
public gathering	0.148	
priority protection	0.226	
labor-intensive	0.152	
General risk	0.094	

4.2. Fire risk quantification based on the SAVEE model

Kernel density analysis was used to quantify the point data density distribution of various fire risk factors, and the kernel density results were categorized into five levels based on the natural breakpoint method, as shown in Figure 5. The spatial heterogeneity of fire risk was further quantified using the SAVEE model. Firstly, different standardized equations are selected according to the different nature of fire risk factors, see equations (1) to (4). Using Python syntax to construct and execute statements, the normalized values after weights were operated by iterative equations in two iterations. The results were categorized into 10 grades using the equal interval method to obtain the spatial distribution of fire potential risk zones in the study area, as shown in Figure 6. The grading results were sorted from high to low, and the areas and occupancies are shown in Table 3.

Analyzing the top 10% fire potential high risk area, it is mainly distributed in the range of 3500m radius with Nanping Pedestrian Street as the circle center, and also distributed in the range of 500m radius with the People's Government of Guandu District as the circle center. Nanping Pedestrian Street is an old neighborhood in the history of Kunming, one of the busiest neighborhoods in Kunming, and this area is mostly in the category of public gathering and key protection, with high fire hazards.

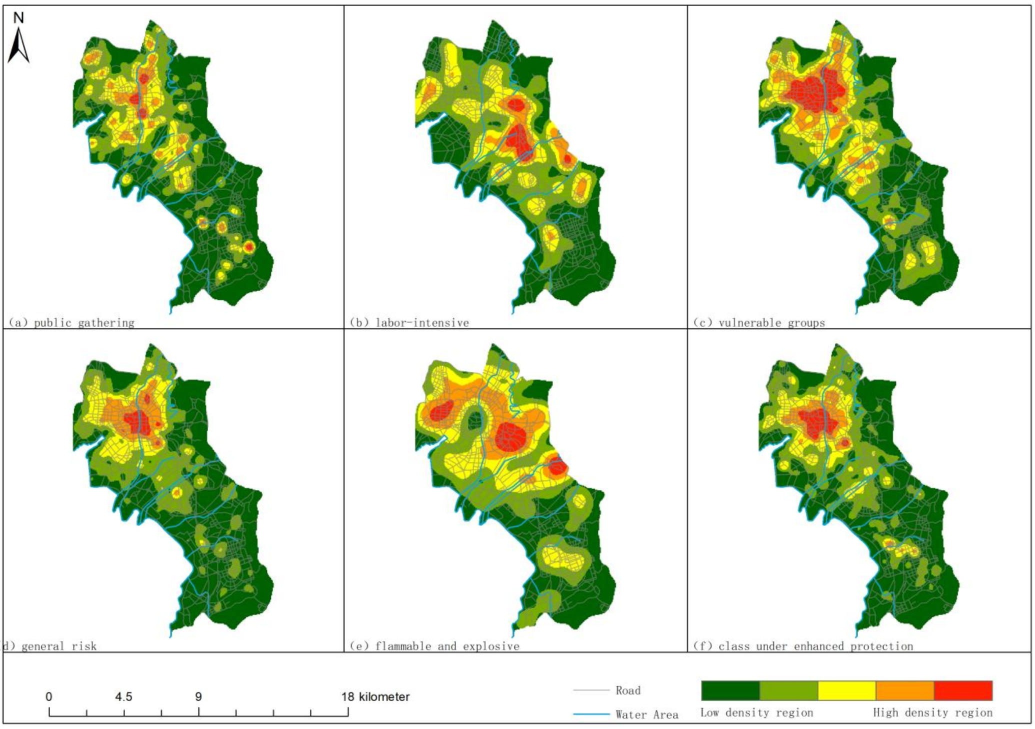

Figure 5. Kernel Density Distribution of Potential Fire Risk Factors

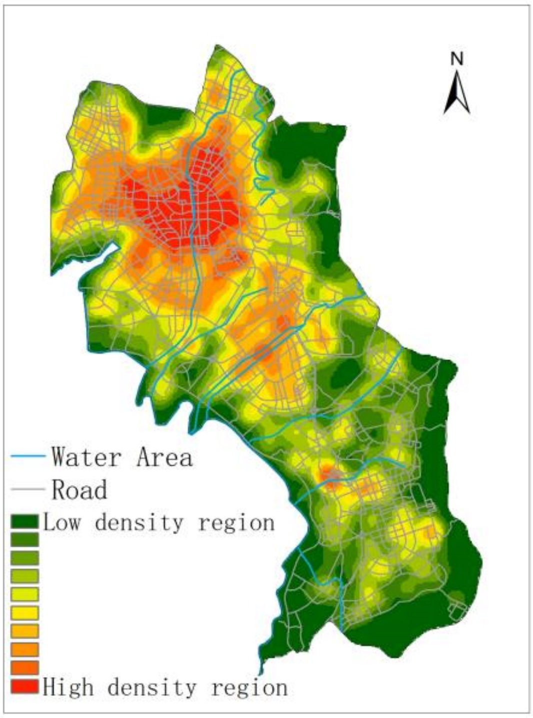

Figure 6. Spatial Distribution of Potential Fire Risk Areas

Table 4. Area and Proportion of Potential Fire Risk Areas

Type of risk area	Classification of potential risk areas	Area/km²	Percentage (%)
latent risk area	1	58.97	11.86
	2	61.81	12.43
	3	57.23	11.51
	4	60.75	12.22
	5	56.76	11.42
	6	45.49	9.15
	7	46.10	9.27
	8	46.19	9.29
	9	32.06	6.45
	10	31.79	6.39

4.3. Quantification of fire station siting suitability factors based on the SAVEE model

Due to the limitations of real factors and the fire fighting needs of different cities, to ensure that the fire station can respond faster to the fire events in a specific area, this paper makes a comprehensive assessment of the land conditions, environmental factors, urban planning and other factors that need to be considered when selecting the location of the fire station to get the appropriate factors for the location of the fire station, taking into account that the different factors have different impacts on the location of the fire station, the AHP hierarchical analysis is used to evaluate the factors of each type, see Table 4. Considering that different factors have different influences on the location of fire stations, AHP hierarchical analysis is used to evaluate the various factors, see Table 4, and the density analysis of the appropriate factors for the location of fire stations is carried out, and the density values are graded by the natural discontinuity method, as shown in Fig. 7. Each factor selects different standardized equations according to different properties, and the standardized values after weighting are calculated by iterative equations with two iterations. The result is divided into 5 levels by equal interval grading method, excluding areas with slope greater than 8°, within 200m buffer zone of hazard sources and land types that cannot be used for construction (Fig. 8), and finally obtaining the distribution of suitable zones for fire station siting in the study area, as shown in Fig. 9. The area suitable for fire station siting in the study area is 430.40km^2, accounting for 83.62%.

Table 5. Evaluation Indicators and Weights for the Suitability of Fire Station Location Selection

considerations	weights	(an official) standard	weights	Sub-criteria	weights	CR	Final weighting
matrix	0.500	population density	0.800	≤52.0	0.281	0.002	0.112
				52.0-152.0	0.241		0.096
				152.0-263.0	0.206		0.082
				263.0-381.0	0.15		0.060
				＞381.0	0.122		0.049
		Distance to water source	0.200	≤437.3	0.281	0.002	0.028
				437.3-997.1	0.242		0.024
				997.1-1679.3	0.202		0.020
				1679.3-2606.5	0.151		0.015
				＞2606.5	0.124		0.012
socio-economic	0.500	elevation	0.158	≤8.0	0.8	0.001	0.063
				＞8.0	0.2		0.016
		road density	0.299	≤0.9	0.297	0.010	0.044
				0.9-1.8	0.246		0.037
				1.8-2.6	0.196		0.029
				2.6-3.4	0.152		0.023
				＞3.4	0.109		0.016
		Distance from road	0.237	≤151.7	0.297	0.010	0.035
				151.7-479.6	0.246		0.029
				479.6-922.6	0.196		0.023
				922.6-1561.5	0.152		0.018
				＞1561.5	0.109		0.013
		Distance to hazardous sources	0.306	≤595.3	0.286	0.009	0.044
				595.3-1089.0	0.223		0.034
				1089.0-1626.3	0.189		0.029
				1626.3-2308.7	0.169		0.026
				＞2308.7	0.133		0.020

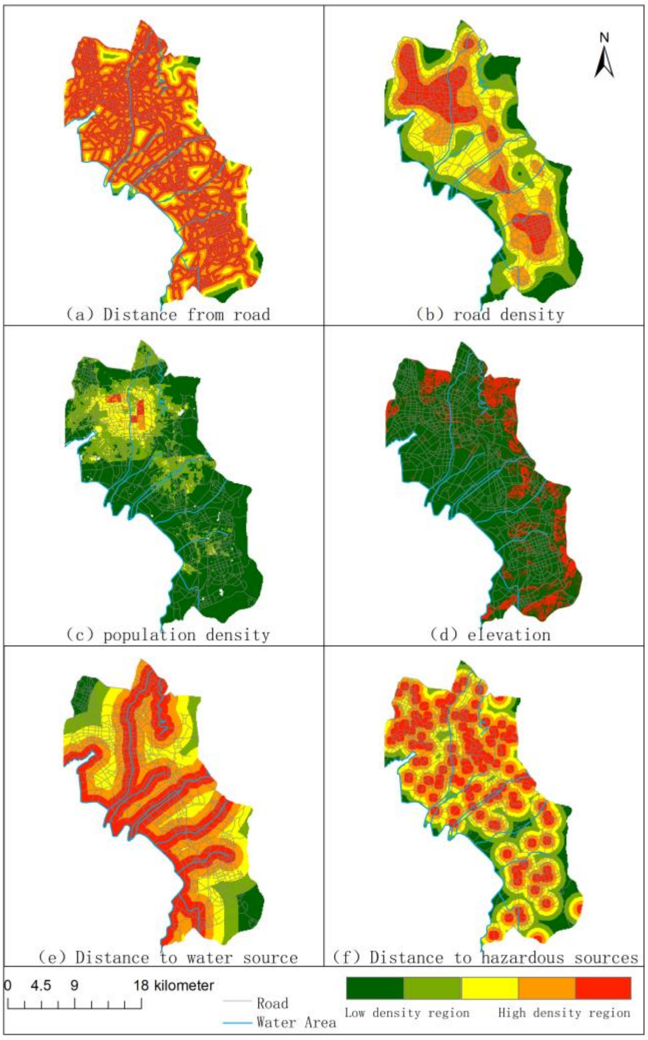
(a) Distance from road
(b) road density
(c) population density
(d) elevation
(e) Distance to water source
(f) Distance to hazardous sources

Figure 7. Density Distribution of Suitable Factors for Different Types of Fire Station Location Selection

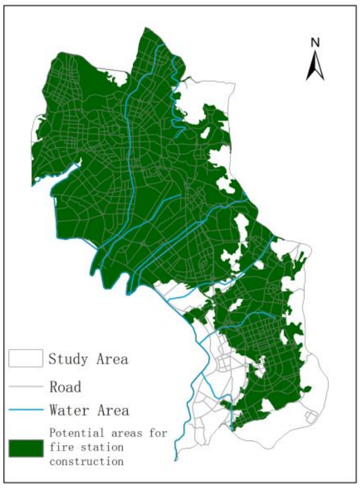

Figure 8. Land Use for Potential Fire Station Construction

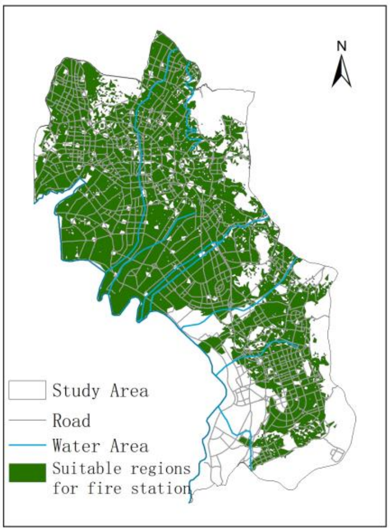

Figure 9. Suitability Evaluation of Land Use for Fire Station

5. Spatial Optimization of Fire Stations

5.1. Status of fire station coverage

According to the 5min response principle, we evaluated the 20 existing fire station sites in the study area to maximize the coverage (Figure 10), and the evaluation results showed that: 1) in terms of the overall coverage of POI points: the existing fire stations cover 29013 POI points, with a coverage rate of 71.47%, and the overall coverage is average; 2) in terms of the spatial distribution of coverage: the coverage in the northwestern and northern parts of the study area is is better, and POI coverage in the central region is worse. It is worth noting that the density of POI points in the central region itself is relatively low, which to some extent affects the effectiveness of its coverage.3) Coverage of various types of fire potential risk zones: the coverage rate of the existing fire stations for the first 10% of the fire high-risk zones is 96.81%, for the first 30% of the fire high-risk zones is 77.59%, and for the first 50% of the fire high-risk zones is 73.47%. fire high risk zone coverage is 73.38%, the uncovered POIs within the fire high risk zone are mainly concentrated in the areas on the edge of the set coverage percentage range, the coverage of the top 10% fire high risk zone is better, but the coverage of the top 30% fire high risk zone has dropped significantly, by 19.22%.

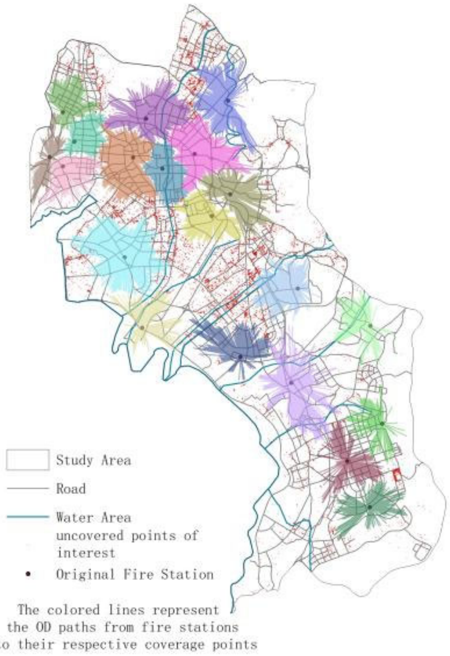

Figure 10. Maximum Coverage Area of Existing Fire Stations

5.2. Fire station space siting

Theoretically any point of the construction land in the central city may have fire, but this modeling workload is too large and the study is not scientific and reasonable [14]. In this paper, based on the results of the analysis of fire station siting suitability area, using the ArcGIS fishing net tool, the fire station siting suitability area is divided into 1515 500m grids, and the center point of each grid is defined as the fire station candidate point. Through the model of minimizing the number of facilities, the POI coverage rate is 91.22% at this time, which is improved by 19.75%, and basically full coverage is achieved within 5min response time, the station optimization layout is completed, and the planning site is shown in Figure 11.

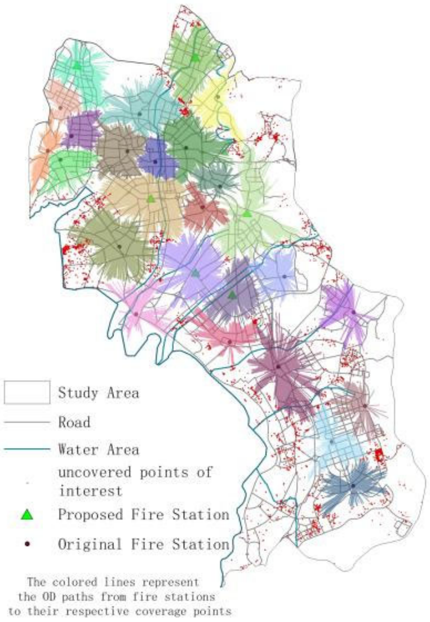

Figure 11. Final Optimization Results

6. Discussion and Conclusions

6.1. Discussion

Fire safety is an important cornerstone of social stability and economic development, and optimization of urban fire station siting layout is an effective means to improve urban rescue capability and safeguard urban safety. In this paper, POI location data is used to realize a more accurate and quantitative perception of urban fire safety conditions, optimize the spatial distribution of fire stations based on different urban natural and socio-economic conditions by mining suitable factors for fire station siting, which is of positive significance to improve the local emergency response speed of firefighting, enhance the ability of urban safety and security, and provide a scientific basis for long-term urban planning. However, the city is an open and complex system, and there are still many deficiencies in the research process of this paper, such as: the road impedance needs to be set up in a more refined simulation; real-time road conditions can be taken into account when simulating the fire trucks; for large buildings, the use of a single POI to replace the actual footprint is too large an error; the model of minimizing the number of facilities is applicable to the present study area, but the applicability to other study areas is still to be verified. The applicability of the model of minimizing the number of facilities to this study area and to other study areas remains to be verified.

6.2. Conclusion

The spatial optimization study of fire station siting in the study area was carried out with the help of AHP hierarchical analysis, SAVEE model and the model of minimizing the number of facilities from the point of view of economy and practicability, and the conclusions are as follows:

Spatial identification of fire potential risk areas and suitable areas for fire station siting in the study area was carried out.

Quantitative calculation obtained the distribution of fire potential risk in the study area: the top 10% fire potential risk areas are mainly distributed around Nanping Pedestrian Street in Wuhua District and the People's Government of Guandu District, which are densely populated with protection sites, and their spatial distribution makes the optimization of fire station site selection more targeted. Study the spatial distribution of suitable areas for fire station siting, eliminating the non-constructable fire station areas, making the selection of fire station candidates more refined, and the spatial optimization of fire stations in different cities more practical.

(2) The existing fire station sites in the study area are sparse, and the existing 20 fire stations are required to cover an area of 514.68km2 of the study area, with a much wider actual area under their jurisdiction. Although the coverage of the top 10% fire potential risk area is better, 96.81%, the overall coverage is poor, only 71.47% of POI points can be effectively covered, and the area around Mile Temple-Yunnan Province Market Supervision Administration, i.e., the central and western parts of the study area are under-covered. In order to improve the fire safety level of the city, it is necessary to plan for the construction of a new fire station and spatial optimization of the fire station sites.

(3) Considering the overall POI coverage rate for the spatial optimization of fire station sites, it was finally concluded that 6 new fire station sites were needed, and the POI coverage rate of the new fire station determined by the model of minimizing the number of facilities increased by 19.75% compared with that of the existing fire station, which was the optimal result of the layout planning of the fire station.

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