GIS-based Fire Risk Assessment and Fire Station Site Selection——Taking Dujiangyan City as An Example

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Abstract. This study takes the urban area of Dujiangyan City as the research area, ten risk assessment factors are selected to conduct the fire risk assessment and analysis, including substations, building floor area ratios and miniature fire stations, and uses analytic hierarchy process, buffer analysis and overlay analysis. The minimize facilities model and maximize coverage model in location allocation model (LA model) are used to optimize fire station site selection. The research results show that there are still greater fire risks in the south and northeast of Dujiangyan City. The addition of two small and medium-sized fire stations in the north section of Yanhua road and in south section of Rainbow Avenue can basically realize to cover the areas with higher fire risks thoroughly.

1. Introduction

Traditional fire station site selection is mostly based on the nature of land usage determined by urban planning. The fire station is the center of the circle, and the farthest distance that the fire truck can reach in 5 minutes is the radius. The area covered by the circle is the fire station’s responsibility area. The single circled area ignores the factors that can affect the risk of fire such as road length, population density, and building density. Ignorance of these potential factors will lead to problems such as unreasonable site selection, large jurisdictional area, and waste of resources in the site selection of fire stations.

With the popularization of geographic information technology, many domestic scholars have used GIS to analyze the location of fire stations. In 2018, Zhu Mingming, Luo Jing and others used points of interest (POI) on electronic maps as the research object to calculate the weights to determine the areas with high fire occurrences in cities [1]. Wu Zaidong, Hu Yujuan and others used AHP and fuzzy mathematics to conduct public safety risk assessment on cultural blocks in 2016 [2]. Peng Zijia and Wu Sijian provided a new mathematical algorithm for the site selection of fire stations in small and medium-sized cities by establishing a mathematical model of load distance [3]. Most of these research methods consider many factors that affect the location of fire stations, such as road factors, building density, population density, flammable and explosive buildings, making the location of fire stations more scientific and strategic in traditional planning methods.
2. Data sources and research methods

2.1. Data Sources
The data used in the research is mainly obtained through field research, network downloading, etc. The geographic location information of the existing secondary fire stations, micro fire stations, and sensitive units is mainly obtained through field research. The population data for the time period is obtained online big data on population density of Easygo in Dujiangyan urban area in 2019. Buildings, roads and other required layer data are mainly downloaded from the 17-level remote sensing image LocaSpaceViewer, and some building outlines are obtained from OpenStreetMap and Bigmap. The spatial reference information of all data needs to be unified into the Xi’an 80 coordinate system.

2.2. Analytical Hierarchy Process (AHP)
The principle of Analytic Hierarchy Process is to divide the problem to be solved into the target layer, the criterion layer and the solution layer. By subjectively comparing the importance of the elements of each layer, the importance weight value of each element is obtained, which can provide data for the grid calculation. Based on the occurrence conditions, potential factors and remedial measures of urban fires, this research divides urban fire risks into three aspects for assessment: dangerous elements (substations, gas stations, chemical plants), urban area environment (population density, key protection units, floor area ratio, traffic network density, water area), fire protection (mini fire station, fire station).

2.2.1. Determine the weight of the evaluation factor.
In this study, C1-C10 are used to represent substations, gas stations, chemical plants, population density, key protection units, floor area ratio, traffic network density, water areas, miniature fire stations and fire stations. W represents the evaluation factors obtained by analytic hierarchy process according to the evaluation criteria for the importance of evaluation indicators in the analytic hierarchy process, the importance of the above evaluation factors is compared in pairs to construct a judgment matrix (see Table 1).

| C1-C1j | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 | W   |
|--------|----|----|----|----|----|----|----|----|----|-----|-----|
| C1     | 1  | 1/2| 1/3| 1/2| 1/2| 1/4| 1/2| 1  | 1/5| 1/6  | 0.0345 |
| C2     | 2  | 1  | 1/2| 1/2| 1  | 1/4| 1/3| 2  | 1/3| 1/4  | 0.0494 |
| C3     | 3  | 2  | 1  | 1/2| 1  | 1/2| 1/3| 3  | 1  | 1/5  | 0.0719 |
| C4     | 2  | 2  | 2  | 1  | 3  | 1  | 2  | 4  | 2  | 1/4  | 0.1266 |
| C5     | 2  | 1  | 1  | 1/3| 1  | 1/2| 1/2| 2  | 1/4| 1/4  | 0.0554 |
| C6     | 4  | 4  | 2  | 1  | 2  | 1  | 3  | 4  | 2  | 1/2  | 0.1546 |
| C7     | 2  | 2  | 3  | 1/2| 2  | 1/3| 1  | 3  | 2  | 1/2  | 0.1106 |
| C8     | 1  | 1/2| 1/3| 1/4| 1/2| 1/4| 1/3| 1  | 1/3| 1/5  | 0.0321 |
| C9     | 5  | 3  | 1  | 1/2| 4  | 1/2| 1/2| 3  | 1  | 1/4  | 0.1026 |
| C10    | 6  | 4  | 5  | 4  | 4  | 2  | 2  | 5  | 4  | 1    | 0.2623 |

The weight value of each evaluation factor C1-C10 calculated by AHP algorithm is 0.0345, 0.0494, 0.0719, 0.1266, 0.0554, 0.1546, 0.1106, 0.0321, 0.1026, 0.2623. The maximum characteristic root of the above judgment matrix is λmax=10.6286 according to formulas (1) and (2).

\[ CI = \frac{\lambda_{max} - n}{n-1} \]  
\[ CR = \frac{CI}{RI} \]
The consistency test of the judgment matrix shows that $CI=0.0698$, $CR=0.0469<0.1$, so the evaluation factor weight obtained by the analytic hierarchy process is more reasonable.

2.2.2. Rating factor classification.
Since the units of the evaluation factors and the degree of influence on the fire risk are different, it must be normalized. According to the relevance of evaluation factors to fire risk, refer to relevant literature and expert scores are used to classify the various factors of fire risk assessment, as shown in Table 2, and the spatial analysis results are shown in Figure 1 to Figure 10.

| Evaluation factor grade | Transformer substation (m) | Petrol station (m) | Chemical plant (m) | Plot ratio | Road network density | Population density | Protection units (m) | Water area (m) | Fire station (m) | Micro volunteer fire station (m) |
|-------------------------|---------------------------|-------------------|-------------------|------------|---------------------|-------------------|---------------------|----------------|----------------|-----------------------------|
| 1                       | >300                      | >100              | >2000             | <1.5       | >14.2               | <0.07             | >200                | <20            | <500           | <50                        |
| 2                       | 200-300                   | 200-1000          | 1000-2000         | 1.5-2.5    | 9.7-14.2            | 0.07-0.22         | 100-200             | 20-50          | 500-1000       | 50-100                     |
| 3                       | 100-200                   | 50-200            | 500-1000          | 2.5-3.5    | 5.8-9.7             | 0.22-0.39         | 50-100              | 50-100         | 1000-2000      | 100-200                    |
| 4                       | 50-100                    | 20-50             | 200-500           | 3.5-4.0    | 2.2-5.8             | 0.39-0.58         | 20-50               | 100-200        | 2000-4000      | 200-400                    |
| 5                       | <50                       | <20               | <200              | >4.0       | <2.2                | >0.58             | <20                 | >200           | >400            | >400                      |

Figure 1. Transformer substations.
Figure 2. Petrol stations.
Figure 3. Chemical plants.
Figure 4. Plot ratio.
Figure 5. Road network density.
Figure 6. Population density.
Figure 7. Protection units.
Figure 8. Waters.
2.3. Location allocation model

The basic principle of location configuration is to select a specified number of facility locations from a specified series of candidate facility locations under the given demand and the spatial distribution of existing facilities, and the selection principle is based on a specific optimization model. The result of the selection is to realize the optimization method of the model setting [4]. In this study, the site selection analysis of the fire station was conducted through the minimized facility model and the maximized coverage model. The model can be expressed as:

\[
\begin{align*}
\text{max} & \quad \sum_{i \in I} w_i y_i \\
\text{s.t.} & \quad \sum_{j \in J} a_{ij} x_j \leq 0 (i \in I) \\
& \quad \sum_{j \in J} x_j = N \\
& \quad x_j \in \{0,1\} (j \in J) \\
& \quad y_j \in \{0,1\} (i \in I) \\
& \quad a_{ij} \in \{0,1\} (i \in I, j \in J)
\end{align*}
\]

I is the set of demand points, J is the set of candidate supply points, Wi is the weight of demand point i (population, demand, etc.), N is the number of supply points, aij, xj and yi are all binary variables.

\[
\begin{align*}
a_{ij} &= \begin{cases} 
1 & \text{Demand point } i \text{ can be covered by candidate point } j \\
0 & \text{otherwise}
\end{cases} \\
x_j &= \begin{cases} 
1 & \text{Demand point } i \text{ can be covered by candidate point } j \\
0 & \text{otherwise}
\end{cases} \\
y_i &= \begin{cases} 
1 & \text{Cover demand point } i \\
0 & \text{otherwise}
\end{cases}
\end{align*}
\]

The objective function equation (3) can maximize the weighted summary of the covered demand points. The constraint equation (4) ensures that when the demand point i can only be covered by the candidate point j, and the candidate point j is selected as the supply point, i could be covered.
Constraint formula (5) restricts the number of supply points to be N. Constraint formula (6)-(8) guarantees that $x_i, y_i, a_{ij}$ are binary valued variables [5].

3. Results and analysis

3.1. Fire risk analysis

Use the weights obtained by the previous analytic hierarchy process to perform weighted overlay analysis on the factor layers, then classify them according to natural breakpoints. The higher the evaluation value score is, the higher the existing fire risk is. The result is shown in Figure 11. The fire risk level is the area of plots IV and V accounted for as high as 46.9%, indicating that there are still certain fire hazards in the main urban area. The fire risk in the southeast and northeast of the city is relatively higher. The preliminary analysis reason is the large area of dangerous chemical plants gathered in Puyang Town and the distance from the nearest fire station. The higher fire risk in the eastern and southern areas outside the Second Ring Road is due to the large amount of residential land, dense population and buildings, which can cause the greater possibility of fire. However, there is no fire station in the south and it is close to the suburbs. The road network density is low, and it takes longer time for firefighters to reach this area.

| Fire risk level | Evaluation score | Area/km² | Percentage |
|-----------------|------------------|----------|------------|
| I (low)         | 4.1-6.9          | 3.47     | 8.40%      |
| II (lower)      | 6.9-7.6          | 8.48     | 20.50%     |
| III (medium)    | 7.6-8.2          | 10.01    | 24.20%     |
| IV (higher)     | 8.2-8.8          | 12.17    | 29.42%     |
| V (high)        | 8.8-10.3         | 7.23     | 17.48%     |

Figure 11. Fire risk map.

3.2. Analysis of location of fire station

The urban roads in this study are divided into three levels: main roads, secondary roads, and branch roads. The model attribution table contains these attributes such as road length, grade, and transit time. According to the map, several adjacent buildings are merged into a basic fire-fighting unit, and the
center point of each fire-fighting unit represents the possible location of the fire in the unit. In this study, 967 fire protection units were divided according to the structure of the road network to simulate the location of the fire. And according to the "Urban Fire Station Design Code GB 51054-2014", 262 plots were selected from the unused land in the city as candidate fire station sites. Through the minimum facility model, it can be calculated that at least 5 fire stations can basically achieve the basic coverage of the research area, then the maximum facility model is used to calculate the location of N-1, N, N+1 fire stations, namely the specific site selection when the number of fire stations is four, five, or six, in order to make the horizontal comparison reasonable. The calculation results are shown in Figure 12 to Figure 14.

The coverage ratio of the three existing fire stations is 69.39%, and the number of fire points that failed to arrive on time is 296, which still poses a major safety hazard. With the addition of a fire station, the coverage ratio could be increased to 85.01%, and the number of fire points that could not be reached within 5 minutes was also reduced by 151. If two fire stations are added, the coverage rate can be increased to 93.59%, and the number of missed points will be reduced by 234.

4. Conclusion
This study uses the analytic hierarchy process to carry out fire risk assessment and analysis in Dujiangyan urban area. The results show that the fire risk is higher in the south and northeast areas of the urban area. According to the divided road network structure of different levels and the LA model to calculate the optimal coverage of the five fire stations, the two new fire stations are also consistent with the fire risk assessment results. The site selection and fire risk assessment results have certain reference significance for Dujiangyan’s fire fighting force layout.

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