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# Emergency Material Reserve Location Research in Urban Areas Based on the Supply and Demand Perspective: A Case from China

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## Abstract

In order to improve the scientific layout of urban emergency material reserve, first, considering that the road condition has an important impact on the effect of emergency rescue, the concept of road damage risk factor is introduced in this article to build satisfaction attenuation function based on the thought of demand satisfaction decreasing within the coverage radius; second, based on the maximum coverage model, a multi-objective and multi-repeated cover model was established to solve the limited supply capacity of emergency supplies reserve; finally, the model is verified by using Yanqing district in Beijing. The study's results showed that the improved maximum coverage model can scientifically determine the coverage and quantity of emergency supplies of each emergency material reserve, and improve the efficiency and scientificity of emergency supplies distribution. In order to avoid the disorderly distribution of emergency supplies, it is suggested that the coverage radius and scope of the emergency material reserve should be determined based on the balance between supply and demand.

## Keywords

Emergency Supplies Repository, Multiple Coverage, Location, Network Design

## 1. Introduction

As one of the countries most affected by natural disasters globally, China's eco-

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nomic losses caused by disasters amount to more than 200 billion yuan per year, accounting for about 3% of GDP—more than 100 million people are affected every year. China's emergency services are mainly operated by the government, and emergency facilities are usually built and operated by the government. Among them, as an important part of China's emergency facilities system, the emergency supplies repository plays an important role in emergency rescue; therefore, scientifically and rationally laying out the emergency materials depository has become an important indicator for evaluating the level of China's emergency services. As the emergency services are a part of public service, the primary goal of development is to maximize the coverage of users of emergency services.

Given the extensive operations research literature on facility location problems, at present, the location problem can be divided into the p-median problem, p-center problem, coverage problem, interception problem, etc. Here, coverage research is the most extensively explored area, especially in the field of emergency facilities location. Considering the study object of this paper, this paper focuses this review on recent studies related to the location of emergency facilities.

The location of emergency facilities was first elaborated by Dr. Berin. *et al.* [1] in his doctoral thesis; subsequently, many scholars have studied this issue from different perspectives and obtained a series of research results. Classic examples include Larson *et al.* [2], who constructed the hypercube model and its extension model; additionally, Marianov *et al.* [3] and Drezner *et al.* [4] systematically reviewed the location of emergency facilities at different times. Early research literature considered fewer influencing factors, and it was generally assumed that emergency events such as natural disasters would not cause damage to roads, emergency facilities, and so on. With the deepening of research in this field, scholars have relaxed the above hypothesis; for example, Drezner *et al.* [5] proposed the basic model. Subsequently, Drezner *et al.* [6] constructed a minimum-maximum-regret model that considers multiple objectives based on the multi-objective method and the trade-off between the number of facilities, coverage radius and population percentage. Sun *et al.* [7] constructed a network collaborative location model for an emergency materials depository based on the infectious disease diffusion model. Gollowitzer *et al.* [8] constructed an integer programming model that can be widely used in the emergency response processes of various facilities. In order to improve the scientific nature of emergency facility location results, scholars have carried out a series of extended research works from the following two perspectives.

1) An extension of the concept of "coverage" in the traditional coverage problem. Whether the demand point is covered depends on the coverage radius: if the demand point is within the coverage radius it is covered; otherwise, it is not covered. Considering the shortcomings of this assumption in practical applications, scholars have enriched and perfected this assumption from different angles, including concepts such as gradual coverage, alternate coverage, multiple

coverage and so on. For example, Drezner T first proposed the concept of gradual coverage. Berman *et al.* [9] [10] [11] [12] [13] refined this concept, extending this concept from a binary assumption to a multivariate assumption, and giving a variety of regression functions. Eiselt *et al.* [14], Zhang *et al.* [15], Kalcsics *et al.* [16] and Budge *et al.* [17] have studied and verified the gradual coverage problems from different perspectives. In addition, Daskin *et al.* [18] first proposed the concept of spare coverage; later, Araz *et al.* [19], Erdemir *et al.* [20] and other scholars further developed this concept.

2) Multi-objective emergency facility location research. Considering the limitation of single objective settings in practical application, scholars have also made progress in the research into multi-objective decision models for different research objects. For example, Badri *et al.* [21] considered various conflicting objectives in the location of fire stations, constructing a dual-objective emergency facility location model that took both distance and time objectives and related cost objectives into account. Gupta *et al.* [22] considered the objectives of service time objectives and the connectivity between facilities. Shishebori *et al.* [23] constructed a mixed integer nonlinear programming model that considered transportation cost, path construction cost and other objectives.

From the above, although scholars have made progress in the study of emergency facility locations, there are still two deficiencies: one is the mathematical representation of coverage function, which at present is generally determined on the basis of the distance or travel time between the emergency facility point and the emergency demand point, while the impact of potential road damage on the distribution of emergency materials is often ignored; secondly, the match between the supply capacity of emergency supplies and the demand is neglected. Therefore, this paper first introduces the road damage risk coefficient and constructs a demand satisfaction function based on the traditional concept of coverage function; secondly, on the basis of the idea of "duplicate cover", from the perspective of supply and demand, a multi-objective and multi-repeat location model of urban emergency material depositories is established. This is the main difference between this paper and existing research.

## 2. Materials and Methods

Generally, the problem of urban emergency material storage locations involves two kinds of sites: emergency material reserves for emergency supplies, and demand points for receiving emergency supplies. This paper mainly studies the location of emergency material reserves in urban areas where the terrain is relatively complex and there are many potential hidden danger points along the road; to this end, this paper build an location model, determine the quantity of the emergency material reserve in the zone, the service range of each emergency material reserve, the service radius and the quantity of supplies provided by each emergency material reserve to each emergency demand point, and optimize the distribution of emergency material reserve in the region.

After a natural disaster occurs, if the location of the emergency material reserve is destroyed, the emergency supplies required shall be provide by the emergency material reserve at that place; if other emergency demand points within the service scope of the emergency supplies reserve are damaged, the emergency materials shall be allocated from the emergency material reserve warehouse for emergency rescue. In addition, due to the influence of road conditions, the limited transportation capacity and large demand at emergency demand points, in order to meet the demand for emergency supplies at emergency demand points, it is often necessary to provide emergency services from other emergency material reserves. In order to build an operational research model to describe this problem, the following assumptions are made in this paper:

Assumption 1: The location and number of candidate emergency material reserves and emergency demand points are known and distributed discretely in the plane.

Assumption 2: The distance between any candidate emergency material reserves and the emergency demand point is the shortest distance of actual driving and can be calculated by relevant tools.

Assumption 3: The capacity of candidate emergency material reserves is unlimited, but the supply capacity of emergency supplies to each emergency demand point is limited and often less than the demand for emergency supplies at the emergency demand point.

Assumption 4: The emergency material reserve can provide emergency services for multiple emergency demand points, and one or more emergency material reserves are required to provide emergency services to each emergency demand point.

Assumption 5: Due to the constraints of funds and other factors, the number of emergency material reserves is limited and known.

Assumption 6: The service quality of the emergency material reserve to the emergency demand point is affected by the distance between them and the risk factor of the potential road damage.

## 2.1. Demand Satisfaction Function

Considering the shortcomings in the traditional coverage function [24], by introducing the concept of the road damage risk coefficient, the following demand satisfaction function is constructed:

$$f_{ij} = \begin{cases} 1 & d_{ij} = 0 \\ \left(1-\rho_{ij}\right)\left[\dfrac{\max\left(d_{ij}\right)-d_{ij}}{\max\left(d_{ij}\right)}\right]^{\beta} & d_{ij} > 0 \end{cases} \tag{1}$$

where $\rho_{ij}$ is the road damage risk coefficient (referring to roads at county level and above), and "$1-\rho_{ij}$" epresents the potential risk of road damage in natural disasters between emergency facilities and emergency demand points. In this paper, the ratio between the number of road hazard points between the emergency material reserve $j$ and the emergency demand point $i$ and the total number of road hazard points in the entire site selection area is expressed, $\rho_{ij} \in [0,1]$; $\beta$ is the sensitivity coefficient, and $\beta \in [0,1]$; $d_{ij}$ indicates the shortest driving distance between the emergency demand point and the emergency material reserve; $\max\{d_{ij}\}$ is the maximum distance between any emergency material reserve and any emergency demand point.

## 2.2. Multiple Coverage Definition

Unconventional emergencies such as natural disasters are characterized by a low probability, high destructive power, large demand for emergency services, great difficulty in rescue and long influence time. Because of traffic and other factors, the capability of a single emergency facility to provide emergency service to an emergency demand point is usually lower than that of the emergency demand point; therefore, inspired by the concept of time satisfaction proposed by Ma Yun feng [25], this paper defines "coverage" in the traditional multi-repeat cover model as follows:

Multiple coverage: after a disaster, the number of emergency facilities providing emergency services for any emergency demand point $i$ shall be determined by the number of emergency service demands of the emergency demand points ($Q_i$) and the amount of emergency services provided by each emergency facility point ($u_{ij}$).

The following two constraints are implicit in the definition of "multiple coverage":

1) Each emergency demand point needs at least one or more emergency facilities to provide services.

2) The sum of the emergency services provided by all emergency facilities should be greater than or equal to the number of emergency service requirements at the emergency demand point; otherwise, the point is not fully covered.

According to the above definition, compared with the traditional coverage, multi-repeat cover not only increases the stability of the system but also improves the efficiency of the entire emergency network, because, when planning and distributing the amount of emergency service to be provided by each emergency facility to each emergency demand point, the traffic-bearing capacity and other factors between them are fully considered. This can avoid road congestion and other phenomena caused by disorder, which then cause chaos of emergency rescue channels; thus, this ensures the orderliness and continuity of emergency rescue work in disaster areas. See **Figure 1** for details.

As shown in **Figure 1**, when demand satisfaction $f_{11}$, $f_{12}$ and $f_{13}$ are 0.3, 0.2 and 0.1, the demand for emergency material at emergency demand point $I$ is 10, and emergency facilities $J_1$, $J_2$ and $J_3$ provide 7.4 and 5 units of supplies for emergency demand points; according to the definition of multiple coverage in this paper, emergency facilities $J_1$ and $J_3$ provide emergency material for emergency demand point $I$, and meet $Q(10) \le u_{11}(7) + u_{13}(5)$.

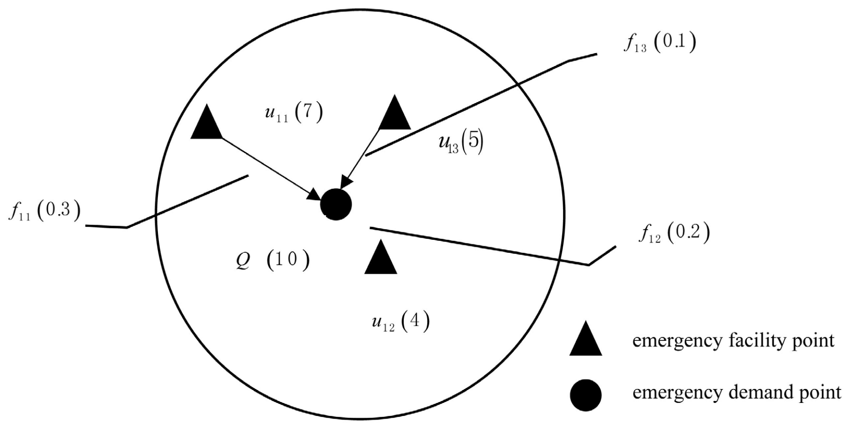


**Figure 1.** Schematic diagram of multiple coverage.

## 2.3. Multiple Coverage Model

In the model built in this paper, let $I = \{I_1, I_2, \cdots, I_m\}$ represent the set of emergency demand points, $J = \{J_1, J_2, \cdots, J_n\}$ represent the set of candidate emergency material reserves, $p$ represent the number of emergency material reserves to be built ( $p \le n$ ), $Q_i$ represent the quantity of emergency supplies required at emergency demand point $i$ (this paper replaces this with the population size of the emergency demand point), $u_{ij}$ represent the quantity of emergency supplies supplied by candidate emergency supplies reserve $j$ to emergency demand point $i$, and $f_{ij}$ represent the level of satisfaction between the emergency demand point and the emergency material reserve. $x_{ij}$ represents the variables 0 and 1: when $x_{ij}$ is 1, this shows that the emergency demand point $i$ is covered by the emergency material reserve $j$; otherwise, it is 0. $y_j$ represents the variables 0 and 1: when $y_j$ is 1, this shows that the candidate emergency material reserve is selected; otherwise, it is 0.

This paper is based on the maximum coverage model constructed by Church [26] and Berman [27], aims to obtain the maximum total satisfaction of covered emergency demand points and the minimum total driving distance; from the known number of candidate emergency material reserves, this paper select emergency material reserve and determine the coverage of the emergency material reserve and the quantity of emergency supplies supplied by the emergency material reserve to each emergency demand point. The multi-objective multiple coverage model is constructed as follows:

$$Z_1 = \max \sum_{i=1}^{m} \sum_{j=1}^{n} Q_i f_{ij} x_{ij} \tag{2}$$

$$Z_2 = \min \sum_{i=1}^{m} \sum_{j=1}^{n} d_{ij} x_{ij} \tag{3}$$

Subject to

$$x_{ij} \le y_j, \forall i \in \boldsymbol{I}, \forall j \in \boldsymbol{J} \tag{4}$$

$$\sum_{j}^{n} x_{ij} u_{ij} \ge Q_i, \forall i \in \boldsymbol{I}, \forall j \in \boldsymbol{J} \tag{5}$$

$$\sum_{j=1}^{n} y_j = p, \forall j \in \boldsymbol{J} \tag{6}$$

$$x_{ij}, y_j \in \{0,1\}, \forall i \in \boldsymbol{I}, \forall j \in \boldsymbol{J} \tag{7}$$

Formula (2) shows the maximum total satisfaction of emergency demand points covered by emergency material reserves in the location area; Formula (3) shows the minimum total travel distance of emergency demand points covered by emergency material reserves in the location area; Formula (4) shows that when candidate emergency material reserve *j* is selected, the emergency demand point *i* can be covered; Formula (5) shows that the sum of the emergency material provided by all emergency material reserves should be greater than or equal to the number of emergency material requirements at the emergency demand point; Formula (6) shows the number of emergency material reserves to be built in the location area; and Formula (7) shows that $x_{ij}$ and $y_j$ are Boolean variables.

### 2.4. Model Simplification

As an important branch of mathematical programming, multi-objective programming is often used to study the optimization of multiple objective functions in a given region, and there is often a conflict relationship between the objectives. There are several ways to solve multi-objective programming: one is to transform multi-objectives into a single objective which is easier to solve, such as by using the linear weighting method, ideal point method, etc.; the other approach is the hierarchical sequence method, which first gives the sequence of the objective according to the degree of importance, and then solves the optimal solution of the next objective in the optimal solution set of the previous objective every time until the final satisfactory solution is calculated.

At present, the weighted method is a common method to solve multi-objective functions. The core of this approach is to solve the problem by transforming the multi-objective model into the single-objective linear programming model by assigning weights to each objective; the multi-objective criterion function is then transformed into a single-objective criterion function, and when $\sum_{1}^{k} \lambda_k = 1$, this represents the commonly used linear weighting method. Under the premise that the total weight is equal to 1, the linear weighting method achieves strong flexibility by assigning different weights according to the importance of each objective. In the process of actual decision-making, decision-makers can obtain multiple sets of different feasible solutions by adjusting the value of weight $\lambda_k$, which can be selected by decision-makers according to different situations; therefore, this paper applies the linear weighting method to transform the model.

Firstly, the objective functions $Z_1$ and $Z_2$ are standardized with uniform measurement standards, meaning that new objective functions $Z_1^*$ and $Z_2^*$ are obtained; then, let $\lambda_1$ and $\lambda_2$ be the weight coefficients of the objective function $Z_1^*$ and $Z_2^*$, and $\lambda_1 + \lambda_2 = 1$. The above model can be converted into the following form:

$$Z = \max\left(\lambda_1 Z_1^* - \lambda_2 Z_2^*\right) \tag{8}$$

Subject to

(4) - (7)

In model (8), if the weight coefficient $\lambda_1 = 0, \lambda_2 = 1$, the above model is transformed into the multi-cover model of public emergency facilities in mountain towns with the objective of the shortest total distance. The model is as follows:

$$Z_2 = \min \sum_{i=1}^{m} \sum_{j=1}^{n} d_{ij} x_{ij} \tag{9}$$

Subject to

(4) - (7)

In model (8), if the weight coefficient $\lambda_1 = 1, \lambda_2 = 0$, the above model is transformed into the multi-cover model of public emergency facilities in mountain towns with the objective of the maximizing the satisfaction of multiple attributes. The model is as follows:

$$Z_1 = \max \sum_{i=1}^{m} \sum_{j=1}^{n} Q_i F_{ij} x_{ij} \tag{10}$$

Subject to

(4) - (7)

In summary, in the study of public emergency facilities locations under unconventional emergencies such as natural disasters, the coverage of emergency services and the operational efficiency of the public emergency facility service network should be considered; therefore, the model constructed in this paper represents an extension of the traditional maximum coverage model.

## 2.5. Immune Optimization Algorithm

The multi-objective multiple coverage model constructed in this paper is an extended model of the maximum coverage model, so it is also an NP-hard problem; for this kind of problem, the traditional accurate algorithm is often powerless, and this paper must generally choose an approximate algorithm or heuristic algorithm to solve the problem. Therefore, this paper chooses the immune optimization algorithm to solve the model. The main steps are as follows.

1) Antibody coding and production of the initial antibody group

In this paper, candidate emergency facility points are encoded by real-number-coding; each location scheme can form antibodies of length p, where each antibody represents the sequence selected as candidate emergency facilities points. Because the immune optimization algorithm needs to start from an initial antibody group, in order to ensure that each candidate point for emergency facilities has an equal opportunity to be selected, N antibodies in the initial antibody group are generated at random; in addition, in order to improve the convergence speed of the algorithm, after each iteration, m antibodies are optimally extracted and put into the memory bank and then combined with the daughter antibodies before the next iteration to obtain a new antibody group.

2) Assigning of fitness

In order to improve the solution efficiency of the model, the following fitness assignment process is designed according to the characteristics of the model:

Step 1: Select the first emergency demand point in order and arrange the quantity of emergency supplies distributed from each candidate emergency material reserve to this emergency demand point in descending order. When the distribution amount of emergency supplies is equal, arrange it according to the degree of satisfaction.

Step 2: Compare the sum of the quantity of emergency supplies distributed from the candidate emergency material reserve (represented by the first $k\left(k=1,2,3,\cdots,p\right)$ genes) to this emergency demand point with $Q_i$; if this is greater than or equal to the demand, find the value of formula 8 at the corresponding position; otherwise, take the value of 0.

Step 3: Repeat steps 1 and 2; after going through all the emergency demand points, the sum is the fitness value of the antibody.

3) Immune operation

This part includes selection, crossover and mutation. Among them, the selection operation uses roulette wheel selection, the crossover operation uses single-point crossover, and the mutation operation uses a random selection of mutation sites.

4) Termination conditions

Record the fitness value of the biggest antibody in each iteration process until the maximum number of iterations set by the algorithm is reached. When the algorithm stops, the antibody with the maximum fitness value is the optimal solution of the problem.

5) Immune optimization algorithm steps

Step 1: Carry out real number coding for the candidate emergency supplies reserve and initialize the parameters (including population size, memory bank capacity, iteration times, crossover probability, mutation probability and diversity evaluation parameters).

Step 2: Generate the initial antibody group. N individuals are randomly generated and m individuals are extracted from the memory bank to form the initial antibody group; because the initial memory bank is empty, N is equal to the population size of the initial value.

Step 3: Diversity assessment of antibodies. In this algorithm, the expected reproduction probability (ps) of the antibody is composed of three values: they are the affinity between antibody and antigen, the affinity between antibody and antibody and the antibody concentration, and ps as a standard to evaluate the antibody.

Step 4: Form a parent group. The initial antibody group is arranged in descending order according to the expected reproduction probability (ps); this paper extract the first N to form the parent generation group, and put the first m individuals into the memory bank.

Step 5: Judge whether the end condition is met: if yes, end it; otherwise, proceed to the next step.

Step 6: After immunizing the individuals in the parent group, the new population is formed together with the individuals in the memory bank, and return to step 3.

## 3. Results

This article validates the above models and ideas based on survey data from Yanqing District, Beijing. Yanqing district, whose geographical coordinates are longitude 115˚44' - 116˚34' and latitude 40˚16' - 40˚47', is one of the most important suburban areas and counties in northwest Beijing. It is surrounded by Huairou district in the east, Changping district in the south, Huailai county in Hebei province in the west, and Chicheng county in Hebei province in the north. At the end of 2015, the resident population was 316,000, with 11 towns and four townships under its jurisdiction. Yanqing district is located in the northeast of the Yanhuai basin, surrounded by mountains on three sides. The terrain of the whole area is complex: mountainous area accounts for 72.8% of the total area, and the plain area amounts to only 26.2%; the average altitude is about 500 meters, and the Haituo mountain, with an altitude of 2241 meters, is the second highest peak in Beijing. The complex terrain makes the region vulnerable to natural disasters such as mudslides, landslides, heavy rain and freezing, which also makes rescue efforts more difficult. According to the emergency plan for sudden geological disasters in Beijing (revised in 2012), the vast majority of geological hazards are far away from the municipal and district governments, and in the event of disasters, roads are often vulnerable to damage; thus, for the county's emergency rescue team, getting equipment and supplies to the scene in a timely manner becomes more difficult, and strengthening and improving the construction of regional emergency material storage is therefore key to dealing with sudden geological disasters.

### 3.1. Data Collection and Parameter Estimation

According to the 12th Five-Year Plan for comprehensive disaster reduction, there is a state emergency plan for natural disaster relief and an emergency plan for sudden geological disaster in Beijing (revised in 2012), along with other documents. In this model, the location of the emergency demand point and candidate emergency material reserves are the location of the government departments of the towns and villages in Yanqing district; the population of each town can be obtained from the 2015 yearbook of the Beijing Yanqing district, the road condition between the emergency demand point and the candidate emergency material reserves can be obtained by the Baidu map, and the distance between them can be measured by the distance measuring function in the Baidu map. In addition, the number of potential hidden danger points in this paper comes from geological hazard points of the Beijing Yanqing district.

In the problem of urban emergency supplies reserve locations, because of the large investment in the construction of the emergency supplies reserve and the low frequency of use, in order to reduce the waste caused by the long-term idle of the emergency supplies reserve, the construction of a proper number of emergency supplies reserves has practical significance. According to the administrative division of Yanqing district, there are 15 towns at present; consulting relevant data, it can be found that the town with the smallest population in Yanqing district is Zhenzhuquan town (3900) and that with the largest population is Yanqing town (37,000), and the maximum driving distance between towns is from Badaling town to Qianjiadian town (74.7 kilometers). According to the principle that the larger the driving distance, the lower the distribution quantity of the emergency supplies reserve to the emergency demand point, this paper assume that the shortest driving distance between the emergency supplies reserve and the emergency demand point is within the range of 0 - 30 km, and the distribution amount of emergency supplies from the emergency supplies reserve to the emergency demand point is between 2000 and 4000 people; when the shortest driving distance is between 30 - 75 km, the distribution amount of emergency supplies from the emergency supplies reserve to the emergency demand point is between 1000 and 2000 people, specific data are shown in **Table 1**. In the model, the weight coefficients of the objective function Z are 0.6 and 0.4, respectively, and the sensitivity coefficient $\beta$ is 0.2. After visiting the emergency management experts of Yanqing district civil affairs at the emergency office and other relevant departments, it is determined that the construction quantity of emergency supplies repositories is 6.

### 3.2. Emergency Supplies Repository Network Design

According to relevant survey data, using Matlab R2013b to write an improved immune optimization algorithm and running it under the Windows 10 system environment of PC, according to the calculation, Yanqing town, Zhangshanying town, Badaling town, Jiuxian town, Sihai town and Dayushu town in the Yanqing district were determined as the construction sites for the emergency supplies reserve; specific configuration results are shown in **Table 2** and **Table 3**.

It can be seen from the fourth column of **Table 2** and the second column of **Table 3** that Yanqing town is the location of the emergency supplies reserve that provides emergency services for Yanqing town, and the maximum service radius is 0 km; Zhangshanying town is the location of the emergency supplies reserve that provides emergency services for Zhangshanying town, and the maximum service radius is 0 km; Badaling town is the location of the emergency supplies reserve that provides emergency services for Badaling town, and the maximum service radius is 0 km; Jiuxian town is the location of the emergency supplies reserve that provides emergency services for Jiuxian town, and the maximum service radius is 0 km; Sihai town is the location of the emergency supplies reserve

**Table 1.** Distribution amount of emergency supplies from the emergency supplies reserve to the emergency demand point. Unit: ten thousand people.

| $u_{ij}$ | Yan qing | Zhang shan ying | Kang zhuang | Bada Ling | Yong ning | Jiu xian | Si hai | Qian Jia dian | Shen Jia ying | Da Yu shu | Jing zhuang | Liu Bin bao | Da Zhuang ke | Xiang ying | Zhen Zhu quan |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Yanqing | 3.7 | 0.35 | 0.38 | 0.34 | 0.3 | 0.4 | 0.27 | 0.14 | 0.36 | 0.4 | 0.32 | 0.28 | 0.23 | 0.31 | 0.18 |
| Zhangshanying | 0.37 | 2.3 | 0.37 | 0.24 | 0.19 | 0.26 | 0.14 | 0.12 | 0.28 | 0.22 | 0.29 | 0.13 | 0.12 | 0.21 | 0.11 |
| Kangzhuang | 0.39 | 0.36 | 2.15 | 0.38 | 0.18 | 0.23 | 0.13 | 0.1 | 0.3 | 0.33 | 0.22 | 0.14 | 0.13 | 0.16 | 0.1 |
| Badaling | 0.39 | 0.26 | 0.38 | 0.71 | 0.19 | 0.22 | 0.15 | 0.11 | 0.27 | 0.28 | 0.21 | 0.13 | 0.12 | 0.14 | 0.12 |
| Yongning | 0.39 | 0.2 | 0.2 | 0.2 | 2.5 | 0.4 | 0.34 | 0.12 | 0.35 | 0.32 | 0.22 | 0.38 | 0.21 | 0.39 | 0.16 |
| Jiuxian | 0.38 | 0.31 | 0.28 | 0.33 | 0.31 | 2.3 | 0.16 | 0.15 | 0.36 | 0.24 | 0.26 | 0.34 | 0.18 | 0.35 | 0.17 |
| Sihai | 0.11 | 0.13 | 0.18 | 0.12 | 0.26 | 0.12 | 0.72 | 0.16 | 0.16 | 0.16 | 0.2 | 0.36 | 0.14 | 0.26 | 0.39 |
| Qianjiadian | 0.11 | 0.14 | 0.13 | 0.12 | 0.14 | 0.2 | 0.2 | 1.14 | 0.35 | 0.36 | 0.33 | 0.18 | 0.2 | 0.36 | 0.19 |
| Shenjiaying | 0.4 | 0.37 | 0.26 | 0.29 | 0.29 | 0.35 | 0.12 | 0.1 | 1.14 | 0.24 | 0.21 | 0.34 | 0.14 | 0.36 | 0.17 |
| Dayushu | 0.39 | 0.2 | 0.4 | 0.34 | 0.21 | 0.3 | 0.17 | 0.11 | 0.34 | 1.5 | 0.26 | 0.24 | 0.18 | 0.34 | 0.12 |
| Jingzhuang | 0.28 | 0.21 | 0.22 | 0.31 | 0.26 | 0.39 | 0.15 | 0.14 | 0.31 | 0.26 | 1.19 | 0.35 | 0.32 | 0.22 | 0.14 |
| Liubinbao | 0.23 | 0.13 | 0.2 | 0.17 | 0.35 | 0.26 | 0.4 | 0.17 | 0.23 | 0.38 | 0.21 | 0.77 | 0.27 | 0.35 | 0.27 |
| Dazhuangke | 0.14 | 0.13 | 0.2 | 0.17 | 0.26 | 0.14 | 0.12 | 0.17 | 0.17 | 0.12 | 0.28 | 0.22 | 0.58 | 0.22 | 0.12 |
| Xiangying | 0.3 | 0.27 | 0.16 | 0.13 | 0.38 | 0.33 | 0.24 | 0.14 | 0.25 | 0.28 | 0.34 | 0.36 | 0.21 | 0.85 | 0.19 |
| Zhenzhuquan | 0.1 | 0.11 | 0.13 | 0.18 | 0.11 | 0.1 | 0.36 | 0.17 | 0.16 | 0.16 | 0.16 | 0.2 | 0.11 | 0.17 | 0.39 |

Note: rows show the emergency demand points, columns show the candidate emergency supplies reserves.

**Table 2.** Results for emergency supplies reserves in Yanqing district. Unit: ten thousand people.

| Emergency demand point | The number of people in need of emergency supplies | The actual number of people supplied with emergency supplies | Provided service of emergency supplies reserve (supply population) |
|---|---|---|---|
| Yanqing | 3.7 | 3.7 | Yanqing (3.7) |
| Zhangshanying | 2.3 | 2.3 | Zhangshanying (2.3) |
| Kangzhuang | 2.15 | 1.99 | Yanqing (0.38), Zhangshanying (0.37), Badaling (0.38), Jiuxian (0.28), Sihai (0.18), Dayushu (0.4) |
| Badaling | 0.71 | 0.71 | Badaling (0.71) |
| Yongning | 2.5 | 1.46 | Yanqing (0.3), Zhangshanying (0.19), Badaling (0.19), Jixian (0.31), Sihai (0.26), Dayushu (0.21) |
| Jiuxian | 2.3 | 2.3 | Jiuxian (2.3) |
| Sihai | 0.72 | 0.72 | Sihai (0.72) |
| Qianjiadian | 1.14 | 0.79 | Yanqing (0.14), Zhangshanying (0.12), Badaling (0.11), Jiuxian (0.15), Sihai (0.16), Dayushu (0.11) |
| Shenjiaying | 1.14 | 1.34 | Yanqing (0.36), Jiuxian (0.36), Dayushu (0.34), Zhagshanying (0.28) |

**Continued**

| | | | |
|---|---|---|---|
| Dayushu | 1.5 | 1.5 | Dayushu (1.5) |
| Jingzhuang | 1.19 | 1.34 | Yanqing (0.32), Zhangshanying (0.29), Jiuxian (0.26), Dayushu (0.26), Badaling (0.21) |
| Liubinbao | 0.77 | 0.98 | Jiuxian (0.34), Sihai (0.36), Yanqing (0.28) |
| Dazhuangke | 0.58 | 0.59 | Yanqing (0.23), Jiuxian (0.18), Dyushu (0.18) |
| Xiangying | 0.85 | 1 | Jiuxian (0.35), Dayushu (0.34), Yanqing (0.31) |
| Zhenzhuquan | 0.39 | 0.39 | Sihai (0.39) |

**Table 3.** Coverage of emergency supplies reserve in Yanqing district.

| Emergency demand point | Furthest repository of emergency supplies to provide services/distance | Coverage rate/% |
|---|---|---|
| Yanqing | Yanqing/0km | 100 |
| Zhangshanying | Zhangshanying/0km | 100 |
| Kangzhuang | Sihai/58.7km | 92.5 |
| Badaling | Badaling/0km | 100 |
| Yongning | Zhangshanying/34.7km | 58.4 |
| Jiuxian | Jiuxian/0km | 100 |
| Sihai | Sihai/0km | 100 |
| Qianjiadian | Badaling/74.7km | 69.2 |
| Shenjiaying | Zhangshanying/23.2km | 117.5 |
| Dayushu | Dayushu/0km | 100 |
| Jingzhuang | Zhangshanying/29.0km | 112.6 |
| Liubinbao | Yanqing/25.4km | 127.2 |
| Dazhuangke | Yanqing/36.3km | 101.7 |
| Xiangying | Dayushu/23.5 | 117.6 |
| Zhenzhuqaun | Sihai/5.0km | 100 |

that provides emergency services for Sihai town, and the maximum service radius is 0 km; Dayushu town is the location of the emergency supplies reserve that provides emergency services for Dayushu town, and the maximum service radius is 0 km.

Sihai and Dayushu are the locations of the emergency supplies reserves that provide emergency services for Kangzhuang town; the distance to Sihai town is the furthest (58.7 km). Yanqing, Zhangshanying, Badaling, Jiuxian, Sihai and Dayushu are the locations of the emergency supplies reserves that provide emergency services for Yongning town; the distance to Zhangshaying town is the furthest (34.7 km). Yanqing, Zhangshaying, Badaling, Jiuxian, Sihai and Dayushu are the locations of the emergency supplies reserves that provide emergency services for Qianjiadian town; the distance to Badaling town is the furthest (74.7 km). Yanqing, Jiuxian, Dayushu and Zhangshanying are the locations of the emergency supplies reserves that provide emergency services for Shenjiayng town; the distance to Zhagshanying town is the furthest (23.2 km). Zhangshanying, Jiuxian, Dayushu and Badaling are the locations of the emergency supplies reserves that provide emergency services for Jingzhuang town; the distance to Zhangshanyng town is the furthest (29.0 km). Jiuxian, Sihai and Yanqing are the locations of the emergency supplies reserves that provide emergency services for Liubinbao town; the distance to Yanqing town is the furthest (25.4 km); Yanqing, Jiuxian and Dayushu are the locations of the emergency supplies reserves that provide emergency services for Dazhuangke town; the distance to Yanqing town is the furthest (36.3 km). Yanqing, Jiuxian and Dayushu are the locations of the emergency supplies reserves that provide emergency services for Xiangying town; the distance to Dayushu town is the furthest (23.5 km). Sihai is the location of the emergency supplies reserve that provides emergency services for Zhenzhuquan town, and the maximum service radius is 5.0 km.

From the second and third columns of **Table 2** and the third column of **Table 3**, it can be seen that the population coverage rate of Yanqing town, Zhangshanying town, Badaling town, Jiuxian town, Sihai town, Dayushu town and Zhenzhuquan town is 100%; Shenjiaying town, Jingzhuang town, Liubinbao town, Dazhuangke town and Xiangying town are overcovered, at population coverage rates of 117.2%, 112.6%, 127.2%, 101.7% and 117.6%, respectively; and the population coverage rates of Langzhuang town, Yongning town and Qianjiadian town are poor, at 92.5%, 58.4% and 69.2%, respectively.

## 4. Discussion

The validation of the model's examples shows that multiple coverage models, based on the perspective of supply and demand balance, can help decision makers to scientifically determine the coverage of emergency facilities and the quantity of emergency supplies to avoid disorder in emergency material dispatch. In addition, based on the verification results of the Yanqing District in Beijing, the following three improvements of the emergency facility network in the region can be proposed.

First, when carrying out the overall planning and construction of the emergency supplies reserve in Yanqing district, the distance between the towns, the traffic situation, the potential hidden dangers of main roads and other factors should be taken into consideration; at the same time, it is necessary to rationally plan and determine the quantity of emergency supplies from the emergency supplies reserve to the emergency demand points and to try to avoid traffic jam caused by the large transfer of emergency supplies in order to maximize the operational efficiency of the whole emergency network.

Second, because Yanqing town, Dayushu town, Zhangshanying town and Jiuxian town have the advantages of high traffic convenience, good connectivity with other towns and a wide range of services, it is suggested that Yanqing district should take the emergency supplies reserve of these four towns as a key construction project; in addition, considering that Badaling town is an important tourist attraction and Sihai town is the main provider of emergency supplies for several towns with complicated terrain in northeast of Yanqing distict, it is necessary to build an appropriate scale of emergency supplies reserves to improve the ability to respond to disasters in this region.

Thirdly, when planning and constructing emergency supplies reserves in Yanqing district, according to the location of each emergency supplies reserve, it is necessary to reasonably define the coverage scope, the distribution amount of emergency supplies, and the construction scale of each emergency supplies reserve and its role in the whole emergency network to reduce the waste of resources caused by idle emergency supplies.

## 5. Conclusions

The traditional concept of coverage function is extended in this work by introducing the road damage risk coefficient; furthermore, from the perspective of supply and demand, a location model of urban emergency supplies reserves is obtained. Based on the empirical research into Yanqing district in Beijing, the construction location and coverage of the emergency supplies reserve and the quantity of emergency supplies from the emergency supplies reserve to the emergency demand point are obtained. The results of this study provide a scientific reference for the government of Yanqing district to plan and construct emergency supplies reserves.

In this paper, when studying the location of the emergency supplies reserves, this paper only considers the extension of the concept of coverage function and the quantity of emergency supplies from emergency supplies reserve to the emergency demand point; the safety of candidate points, the capacity of the emergency supplies reserve and other factors are not considered. Therefore, a multi-cover model of the emergency supplies reserve considering the capacity limitation will be an important research direction in the future.

## Author Contributions

Conceptualization, F.W.; Formal analysis, F.W.; Investigation, F. W.; Methodology, F.W.; Project administration, Y.H.; Resources, Y.H.; Supervision, Y.H.; Validation, Y.H.; Visualization, Y.H.; Writing—original draft, L.W.; Writing—review & editing, L.W.

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## Conflicts of Interest

The authors declare no conflict of interest.

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