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A multi-objective approach for optimizing emergency material locations in natural disasters

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A B S T R A C T

In response to the increasing frequency of natural disasters globally, and particularly in the Guangxi Zhuang Autonomous Region, this study aims to optimize the site selection for emergency supplies storage facilities. Traditional methods for predicting emergency supplies demand rely heavily on expert judgment, lacking sophisticated forecasting methodologies, which further complicates research due to the inherent unpredictability of natural disasters. This paper adopts a multi-objective programming approach, leveraging historical data and the proposed emergency supplies demand model to systematically address the spatial layout planning problem of emergency material reserve nodes. After comprehensively considering various factors, including risk, economic, and time-related aspects, a 0-1 integer programming model was established, aiming to fulfill all regional requirements for essential resources within minimal rescue timeframes while minimizing overall costs. Through the application of the AHP-Entropy weight method, data standardization and indicator weighting were conducted, resulting in a hierarchical site selection framework that ensures timely emergency response across the region without incurring prohibitive costs. This study represents a significant contribution to the literature by focusing on the unique challenges and requirements of Guangxi and proposing a tailored approach to optimizing the site selection and layout of emergency supplies storage facilities, thereby enhancing disaster preparedness and response strategies effectively.

A R T I C L E I N F O

Keywords:
Natural disasters;
Emergency rescue;
Emergency supplies storage;
Location optimization;
Risk level;
Grade-based location selection system;
Cross-reginal distribution;
0-1 integer programming model;
Multi-objective optimization;
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1. Introduction

In recent years, the escalating frequency of natural disasters has significantly impeded global sustainable development efforts and the enhancement of living standards [1]. From 1989 to 2018, the world witnessed over 6,300 disasters, including droughts, floods, tropical cyclones, forest fires, and earthquakes, incurring direct economic losses of approximately USD 2.44 trillion [2]. This situation underscores the urgent need for effective disaster prevention and mitigation strategies, drawing widespread attention from academic circles and international bodies. Governments play a crucial role in promoting efficient post-disaster recovery, ensuring the basic needs of affected populations, and maintaining social stability [3].

In this context, the pre-emptive stockpiling of emergency supplies emerges as a critical aspect. The construction and operation of emergency supplies storage facilities are vital for improving disaster response efficiency and reducing disaster risks. These facilities store essential relief supplies and equipment, such as food, drinking water, medical supplies, tents, and other basic necessities, ensuring swift and effective support for disaster-stricken areas. Efficient emergency supplies storage facilities enhance disaster response speed, ensure the reliable supply of relief materials, support ongoing rescue operations during recovery and reconstruction phases, strengthen disaster preparedness, and improve public information and social stability.

Given its unique geographic, topographic, and climatic conditions, particularly in disaster-prone regions such as Guangxi in southern China, the area faces recurrent natural disasters, leading to significant economic and human losses annually. In response, Guangxi has implemented various measures under the aegis of its *Comprehensive Risk Census of Natural Disasters* and the regional government's reports, including a comprehensive risk assessment and the fortification of its emergency supplies support system as outlined in its "14th Five-Year Plan". However, despite the establishment of a province-city-county emergency supplies storage system, issues such as unreasonable overall layout, improper grading of storage facilities, and limited emergency storage capacity persist.

Establishing an emergency material reserve warehouse is fraught with numerous practical challenges. From a financial perspective, the issue of capital investment costs is particularly significant, encompassing not only the substantial initial construction expenses but also the long-term maintenance and operational costs. Additionally, storage conditions must meet stringent safety, stability, and preservation requirements, which involve optimizing available space, controlling environmental factors such as temperature to ensure material quality, and maintaining a safe inventory level to prevent overstock or shortages. The selection of reserve materials presents another critical challenge. It requires comprehensive consideration of the types of emergencies that may occur, the predicted frequency and severity of potential disasters, and the functional requirements of emergency response operations. Simultaneously, precise calculation of storage quantity is essential to balance efficiency with resource utilization, avoiding either excessive inventory waste or inadequate supply during critical moments. Logistics and distribution reliability form another integral component of reserve system functionality. This includes ensuring the safety and efficiency of transportation networks, optimizing delivery routes to minimize logistics costs and delays, as well as maintaining robust information systems for accurate demand forecasting and efficient allocation of resources during emergencies. Personnel management also poses significant demands. It necessitates professional training to enhance emergency response capabilities, coupled with effective team coordination and communication strategies to ensure timely and coordinated resource deployment during crises. Moreover, adherence to relevant policy regulations and standard operating procedures is crucial for ensuring the rationality and effectiveness of reserve systems. However, these policies may be subject to implementation delays or variations in enforcement across regions, which can impact their practical utility. Finally, considerations for sustainability and scalability demand that the reserve system be adaptable to evolving needs and environmental conditions. This requires designing a flexible infrastructure capable of scaling up or down as emergency demands change, while ensuring long-term maintenance capabilities to preserve system functionality over time. Overall, addressing these challenges comprehensively through meticulous resource allocation, advanced technical solutions, and robust institutional frameworks is essential for the successful establishment and operation of an effective emergency material reserve warehouse.

This study is based on a risk-economic-time matching framework to ensure the establishment of storage facilities better meets emergency rescue needs. Scholarly research on the site selection of emergency supplies storage has primarily focused on the site selection target, site selection models and the optimization of facility location model. Early works by Park [4] aimed at minimizing costs, while subsequent studies by Du and Zhou [5] and Banyai [6] developed models prioritizing cost-efficiency in disaster relief and swift response times foundational site selection models, such as the P-median model and P-centre model introduced by Mohamed [7, 8], and the set covering model by Niu *et al*. [9], have laid the groundwork for further research. Further, Radu proposes a cost-efficient solution for the routing network associated with the management of supplier-customer distribution systems [10]. Drezner *et al.* [11] proposed the maximum coverage model, which aims to cover as many demand points as possible with a fixed number of facilities.

Recent advancements have seen the application of these classic frameworks to contemporary challenges, including the optimization of ambulance dispatch locations by Maleki *et al.* [12], emergency reserve sites by Fu and Zhang [13], and the location of ambulances by Sudtachat and McLay [14]. The development of multi-objective location models by Feng and Gai [15], and AlHaffar *et al.* [16], further exemplifies this progression, incorporating factors such as timeliness, cost, and demand satisfaction into the decision-making process. Alvarez-Campana [17] presented a simulation approach to enhance the performance of heuristics for multi-project scheduling. Unlike other heuristics available in literature that use only one priority criterion for resource allocation, this paper proposes a structured way to sequentially apply more than one priority criterion for this purpose. Vicente [18] proposed a method of multi-objective multi-agent reinforcement learning method (MOMARL) to construct a shared policy set. Furthermore, Liu *et al*. [19] based on advanced deep learning techniques, a new simulation model has been developed to address the limitations of conventional approaches by considering multiple factors. The methodologies for solving location optimization models range from exact algorithms, capable of pinpointing optimal solutions, to heuristic approaches designed for more complex scenarios. Notable heuristic techniques include genetic algorithms, NSGA-II, simulated annealing and tabu search, which have been effectively applied to emergency facility location problems. Emerging heuristic algorithms, such as the quantum competition algorithm [20], the simulated biological growth algorithm by Abdul Hanan [21], the variable neighbourhood algorithm by Ye *et al*. [22], and the bacterial foraging algorithm by Cao and Chen [23], each marks a leap forward in optimizing complex computational problems [24]. The refinement of the bi-level programming site selection model through the application of genetic algorithms by Pramudita, Taniguchi, and Qureshi [25] illustrates the adaptability of these methods to debris management challenges. Furthermore, the utilization of the NSGA-II algorithm in selecting locations for emergency supplies and facilities [26, 27] demonstrates the algorithm's effectiveness in addressing critical disaster response needs. In addition, Chanta *et al*. employment of the tabu search algorithm to explore location equity within the medical system [28] underscores the versatile application of heuristic algorithms in fostering fair and efficient resource distribution.

Despite the wealth of research on emergency facility location modelling, studies focusing on specific geographic regions, especially within the disaster-affected areas of the Guangxi Zhuang Autonomous Region, remain scarce. This paper aims to bridge this gap by concentrating on the site selection for emergency supplies storage within Guangxi, proposing and solving optimization models tailored to the unique regional context, and develop an optimized model for the site selection of emergency supplies storage in the Guangxi Zhuang Autonomous Region. By addressing the specific challenges and characteristics of this region, the study aims to enhance the efficiency and effectiveness of disaster response and recovery efforts.

The anticipated contributions of this research include several key areas as follow. The first is enhance disaster preparedness. The study will provide a scientifically grounded site selection model that improves the strategic placement of emergency supplies storage facilities in Guangxi, aiming to enhance the region's overall disaster preparedness. The second is provide policy suggestions, the study offers a valuable insights and recommendations for government in the Guangxi Zhuang Autonomous Region, which can help optimize resource allocation and improve disaster response system. Thirdly, the research offers a wide range of applicability. The methodologies and findings of this study are designed to be adaptable and applicable to other disaster-prone regions globally, thereout contributing to the broader field of disaster management and emergency logistics.

2. Methodology

2.1 Data standardization

Due to the variations in data dimensions and meanings among indicators, it is necessary to standardize them for ease of calculation. Subsequently, the positive and negative attributes of each indicator should be determined, followed by processing the data using the following equations.

For position dimensions:

$$X_{mn} = \frac{x_{mn} - min[x_n]}{max[x_n] - min[x_n]} \tag{1}$$

For negative dimensions:

$$X_{mn} = \frac{max[x_n] - x_{mn}}{max[x_n] - min[x_n]} \tag{2}$$

x_{mn} represents the value of n-th disaster facture in the m-th region, $max[x_n]$ denotes the maximum value of n-th disaster facture, $min[x_n]$ signifies the minimum value of n-th disaster facture, and x_{mn} is the standard value of n-th disaster facture in the m-th region after the processing.

2.2 Weighting method for indicators

The weighted of indicators is the significate elements for system evaluating. And this paper follows scientific and accurate principles and combining subjective and objective methods to calculate the weight of each index.

(1) Analytic Hierarchy Process (AHP): AHP makes pairwise comparisons of indicators, constructs a judgment matrix, and then calculates the weight of each indicator, as shown in Table 1.

$$P = \begin{pmatrix} p_{11} & \cdots & p_{1n} \\ \vdots & \ddots & \vdots \\ p_{n1} & \cdots & p_{nn} \end{pmatrix} \tag{3}$$

p_{ij} is the value of after comparing the materiality level of i and j, and satisfy $p_{ij} > 0$, also $p_{ii} = 1$, $p_{ij} = p_{ji}$.

Table 1 1-9 Scale system

p_{ij}	Comparative Interpretation
1	i is as important as j
3	i is slightly more important than j
5	i is obviously more important than j
7	i is strongly more important than j
9	i is utmost important than j
2, 4, 6, 8	the comparison is intermediate between the above comparisons
the reciprocal of above value	The comparison between j and i

(2) Entropy Weight Method: Diverging the AHP, the Entropy Weight Method is predicated on an objective attribution approach derived from data analytics. The computational sequence unfolds as follows:

First, data normalization is conducted, with the methodology for this standardization process having been delineated earlier. Next, the information entropy for each criterion is calculated:

$$E_j = -\frac{1}{\ln m}\sum_{i=1}^{m} p_{ij} \ln p_{ij} \tag{4}$$

where

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \tag{5}$$

Finally, calculate the weight of each criterion:

$$W_j = \frac{1 - E_j}{\sum_{j=1}^{n}(1 - E_j)} \tag{6}$$

In these equations, m is the number of evaluation areas, E_j is the information entropy of j-th criterion, p_{ij} is the proportion of the i-th area under the j-th disaster factor, and W_j is the weight value of the j-th criterion.

(3) Coefficient of Variation Method

This paper utilizes the Coefficient of Variation Method to calculate the composite weights of indicators. The formula for computing the composite weight is as follows:

$$w = (1 - \alpha)w_i + \alpha w_j \tag{7}$$

Here, w is the composite weight of the indicator, α represents the proportion of the weight calculated by the AHP in the composite weight, w_i is the indicator weight determined by the Entropy Weighting Method, w_j is the indicator weight determined by the AHP. To avoid direct determination by subjective factors, this value is determined by the Coefficient of Variation Method, with the calculation formula being:

$$\alpha = \frac{n}{n-1}\left[\frac{2}{n}(w_1 + 2w_2 + \cdots + \mathrm{n}w_n) - \frac{n+1}{n}\right] \tag{8}$$

In this equation, $w_1, w_2, \ldots, w_n$ are the weights determined by the Analytic Hierarchy Process and then re-sorted in ascending order, and n is the number of indicators.

3. Problem and model

3.1 Problem description

When a natural disaster occurs, the site selection and management of emergency material reserves become critical factors, especially in disaster-prone areas such as Guangxi. The primary emergency reserve repository is the fixed one, while the temporary emergency material reserve repository serves as a supplementary option. The establishment of the temporary emergency material reserve repository depends on the specific disaster situation, whereas the fixed emergency material reserve depot functions as a standardized and centralized storage unit for essential resources during emergencies. The advantage of fixed reserves lies in their regularized management and operations, which can quickly respond to sudden events and reduce the delay in preparation and material distribution during disaster. As this paper focuses on studying fixed emergency supplies reserve repositories, multiple factors need to be considered in their location selection to ensure maximum effectiveness during disasters. Firstly, the layout of these reserves should align with the spatial distribution characteristics of regional natural disasters and ensure that they can effectively meet the demand for emergency materials during major disasters, thereby potentially reducing costs. Additionally, these reserves should be positioned to expedite the delivery of materials to affected areas, thereby minimizing rescue times. From an economic standpoint, the site selection process must consider cost-effectiveness optimization. This includes not only the direct costs of constructing the reserves but also long-term maintenance costs. Hence, when choosing locations for these reserves, it is essential to balance their construction and operational costs against their effectiveness in disaster response.

Therefore, addressing the spatial layout planning problem of emergency material reserve nodes becomes a multi-objective programming challenge involving various factors such as economic cost, social benefit, and social stability. By comprehensively analysing both demand and supply conditions for emergency materials during natural disasters, this study systematically explores several spatial layout issues including node placement optimization, size determination based on risk assessment analysis results , quantity allocation according to population density data, and type classification within a given region's network of emergency material reserves with an aim to fulfil all regional requirements for essential resources within minimal rescue timeframes possible while minimizing comprehensive costs incurred in doing so.

The construction of the site selection model is based on several core considerations:

- Adaption to the actual situation: Emergency stuff storages layout should match with the occurrence of natural disasters for national， provincial, city and county, urban public facilities level, the regional logistics development level and the national security policies, to meet the practical necessity of the assistance.
- Coordinate with current situation: The layout plan should echo with the current comprehensive transportation network and the transportation infrastructure, so that the emergency material reserve mode can seamlessly connect with the logistics infrastructure nodes such as airports, railway or road freight stations, highway networks, and railway networks, to improve the emergency logistics system.
- Cost minimization: While meeting service coverage, the model seeks a solution that minimizes overall costs, including construction and operations costs, by optimizing the local and numbers of warehouses.
- Optimization of response time: The model setting must guarantee that the maximum response time from any warehouse to a service area does not exceed a predetermined threshold, enhancing the efficiency of disaster response.
- Maximization of risk coverage: The model ensure that all high-risk area receive adequate emergency material support in the shortest possible time, based on reginal historical disaster data and potential risk assessments.

3.2 Symbol description

The meaning of the symbols is as follows.

C^1, C^2, C^3: The costs associated with establishing level 1, level 2, and level 3 emergency supplies reserve facilities, respectively
Z_i^1, Z_i^2, Z_i^3: 0-1 variables indicating whether a region is selected as a level 1, level 2, or level 3 emergency supplies reserve facility
p: The transportation price per unit distance and volume
w_{ij}: Emergency supplies transported from region i to region j
W_j: Total disaster relief demand in region j
d_{ij}: The distance between region i and region j
A^1, A^2, A^3: The maximum disaster relief capacities of level 1, level 2, and level 3 emergency supplies reserve facilities, respectively
T_{ij}: Whether region i can reach region j within the specified emergency time
F_j: The comprehensive assessment scores of each region
F^1, F^2: The minimum comprehensive scores required for establishing level 1 and level 2 emergency supplies reserves in each region
R_i: The risk level of each region
R^1, R^2: The risk level standards for establishing level 1 and level 2 emergency supplies reserves in each region

3.3 Model set up

In compliance with the stipulations set forth by the policy documents of Guangxi Province， it is mandated that the emergency supply reserve warehouses should span across every county within the region, that is, within the framework of the emergency supply reserve warehouse distribution system, each area affected by disasters is eligible for emergency supply assistance.

In this study, to meet the policy documents for the full coverage of the region's emergency material reserve requirements, a complicated location model is developed with set coverage model concept and combined mixed integer programming theory. The principle of the model is optimizing the layout the storage location and operational costs of the reserves, while ensure every disaster area can receive necessary emergency material assistant rapidly.

Integer Linear Programming (ILP) and Binary Particle Swarm Optimization (BPSO) methods are proposed to solve the optimum PMU placement (OPP) problem [29]. In this paper, a 0-1 Integer Programming Model is established after comprehensive consideration of risk factors, economic factors, and time factors. Parameters such as the maximum and minimum service capacities of the emergency supply reserve nodes, their associated risk levels, and their utmost service radius are defined within the model. These kinds of parameters show whether an emergency material reserve should be established at a specific site. Each potential node has an associated binary variable: a value of 1 indicates the selection of establishing a reserve, while a value of 0 means not establishing one. Through this binary decision variables, the model can stimulate the on/off nature of the location decision process.

Given the capability of handle complex constrained for the mixed integer programming model, a series of constraints are induced to ensure the effectiveness and the practical applicability of the model.

- Service capacity constraints: base on the comprehensive evaluation score to set maximum capacities for each level reserve node to prevent overload operation.
- Risk level assessment: base on the risk level in different region to evaluate and adjust the node level.
- Service range limitation: since the situation of traffic and delivery prices, a maximum service ranges for each reserve are defined to ensure prompt response to all demand areas.
- Moreover, the model also integration data such as the evaluation value of the node to be selected and the specific stuff demand data from various region. These kinds of data, including but not limited the location, population and traffic situation, play a significant role for determining the priority of each node and its character in emergency response. The evaluation value of the nodes to be selected, the material demand of each region and other relevant data are put into the model and identify an emergency supply reserve node layout scheme which can fulfil the regional layout requirement, the emergency supply reserve demands and minimizes overall operational costs. The model's objective is to minimize the total costs while ensuring that all affected areas receive timely aid. Additionally, several constraints such as resource quotas, service capabilities, and regional accessibility are set within the model to ensure that the proposed solutions are both practical and feasible.

By optimizing the model, the emergency storage net can not only conform to the area layout requirements but also minimize overall operating costs while ensuring that regional demands are met. The solution of the model utilizes advanced algorithmic techniques to ensure find the optimal solution within a reasonable time, including linear programming and branch-and-bound methods. In the future, as emergency demands and policies evolve, the 0-1 Integer Programming Model can be dynamically adjusted through adjustment parameter and constraint condition to fit new requirement, providing effective continuously decision support.

The specific expression of the objective function and constraints in the model is as follows:

$$\min Z = \sum_{i=1}^{m}\left[\frac{\left(C^1 \times Z_i^1\right)}{F_i} + \frac{\left(C^2 \times Z_i^2\right)}{F_i} + \frac{\left(C^3 \times Z_i^3\right)}{F_i}\right] + p \times \sum_{i=1}^{m}\sum_{j=1} w_{ij} \times d_{ij} \tag{9}$$

$$M \times \left(Z_i^1 \times Z_i^2 + Z_i^3\right) - \sum_{j=1}^{m} k_{ij} \gg 0, \forall i,\ \ i \epsilon, m \tag{10}$$

$$\sum_{j=1}^{m} w_{ij} \ll A^1 \times Z_i^1 + A^2 \times Z_i^2 + A^3 \times Z_i^3, \forall i,\ \ i \epsilon, m \tag{11}$$

$$M \times \left(T_{ij}^1 \times Z_i^1 + T_{ij}^2 \times Z_i^2 + T_{ij}^3 \times Z_i^3\right) - k_{ij} \gg 0, \forall i、j,\ \ i \epsilon, m \tag{12}$$

$$\sum_{i=1}^{m} w_{ij} \gg W_j, \forall j,\ \ j \epsilon, m \tag{13}$$

$$F_i \gg F^1 \times Z_i^1, \forall i, \ i\epsilon, m \tag{14}$$

$$F_i \gg F^2 \times Z_i^2, \forall i, \ i\epsilon, m \tag{15}$$

$$R_i \gg R^1 \times Z_i^1, \forall i, \ i\epsilon, m \tag{16}$$

$$R_i \gg R^2 \times Z_i^2, \forall i, \ i\epsilon, m \tag{17}$$

$$Z_i^1 + Z_i^2 + Z_i^3 \ll 1, \forall i, \ i\epsilon, m \tag{18}$$

$$Z_i^1 \epsilon \{0,1\}, \forall i, \ i\epsilon, m \tag{19}$$

$$Z_i^2 \epsilon \{0,1\}, \forall i, \ i\epsilon, m \tag{20}$$

$$Z_i^3 \epsilon \{0,1\}, \forall i, \ i\epsilon, m \tag{21}$$

$$T_{ij} \epsilon \{0,1\}, \forall i, \ i\epsilon, m \tag{22}$$

$$w_{ij} \gg 0, \ i\epsilon, m \tag{23}$$

$$d_{ij} \gg 0, \ i, m \tag{24}$$

In the survey sample, the total number of regions is denoted by m, and the total number of disaster factors is denoted by n. In the proposed model, Eq. 9 delineates the objective function aimed at minimizing the establishment cost of warehouses, including the rescue cost of the first, second and third level emergency warehouse and the rescue cost from region i to region j. Constraint condition Eq. 10 indicates that necessitates the establishment of an emergency supply reserve warehouse in region i if they provide disaster relief services. Constraint condition Eq. 11 indicates that the total disaster relief materials provided by the area selected as the emergency materials reserve shall be in line with its reserve capacity. Constraint condition Eq. 12 obligates that if region i renders emergency services to region j, then region j must be within the service ambit of region i. Constraint condition Eq. 13 mandates that the emergency supplies dispensed from region i to region j are sufficient to meet the emergency requirements of region j. Constraint condition Eq. 14 requires that regions tasked with establishing a level-one emergency supply reserve meet a predefined composite score. Similarly, constraint condition Eq. 15 stipulates that regions establishing a level-two emergency supply reserve achieve a requisite comprehensive score. Constraint condition Eq. 16 limits the establishment of a first-level emergency supply reserve to regions with a disaster risk surpassing a specified threshold. Likewise, constraint condition Eq. 17 confines the creation of a second-level emergency supply reserve to regions exceeding a certain risk level. Constraint condition Eq. 18 asserts that regions designated for emergency supply reserves are restricted to a singular level of reserve capacity. Constraint conditions Eqs. 19-14 specify the permissible range for each variable within the model.

The model design proposed in this study fully considers the characteristics of disasters and the diversity of infrastructure development. By flexibly adjusting key parameters such as disaster risk scores and facility capacity, the model can adapt to different types of disasters and levels of infrastructure. Specifically, the disaster risk score reflects the likelihood of potential disasters in a certain area, while the facility capacity measures the disaster resilience of that area. The dynamic changes of these parameters enable the model to have strong adaptability when dealing with different disaster characteristics.

By optimizing the algorithm or introducing a multi-dimensional evaluation system, the model can adjust the prediction indicators according to the specific needs of the region, thereby ensuring its accuracy and reliability. For instance, in areas with high disaster risks, the model can weigh the risk scores to prioritize the impact of high-risk events; while in regions with lower facility capacity, parameter adjustment can be used to simulate the limitations of disaster resilience.

In the long-term planning and operation of an emergency material reserve warehouse, potential variations in operational expenses and road infrastructure status may arise. These factors offer flexibility for parameter adjustments based on tailored needs or scenarios. Additionally, disaster risk is calculated using historical data spanning a 20-year period, which reflects a high degree of robustness and stability. This foundation ensures reliable model utilization under changing circumstances while maintaining the system's resilience to variations in emergency conditions over time. Moreover, Iulia [30] proposed a robust model predictive control approach for systems affected by two types of disturbances can remove the norm 2 bounded disturbance, it can be adopted in longer-term research.

This flexibility is not only reflected at the theoretical level, but has also been verified through experiments, demonstrating the stability and accuracy of the model under different conditions. This is of great significance for practical applications, as it can provide more targeted and practical decision-making support tools for emergency management departments.

4. Model solving

To solve the model, relevant data need to be organized and calculated systematically, such as the quantification of emergency supply demands, assessment scores of candidate nodes, and the accessibility metrics across different regions.

During the model solution process, the study adopted robust historical data and a comprehensive scoring method. These choices have to some extent ensured the stability and reliability of the model, as shown in Fig. 1.

Specifically, based on reliable historical data, it can be ensured that the training set used was representative and could reflect that the distribution in the real world. Additionally, the comprehensive scoring method not only considers the performance of individual indicators but also comprehensively assesses the overall performance of the model through multiple dimensions (such as economic index, transportation index, etc.). These measures help to reduce the volatility of the model under changes in key parameters, thereby ensuring the robustness and credibility of the model results to a certain extent.

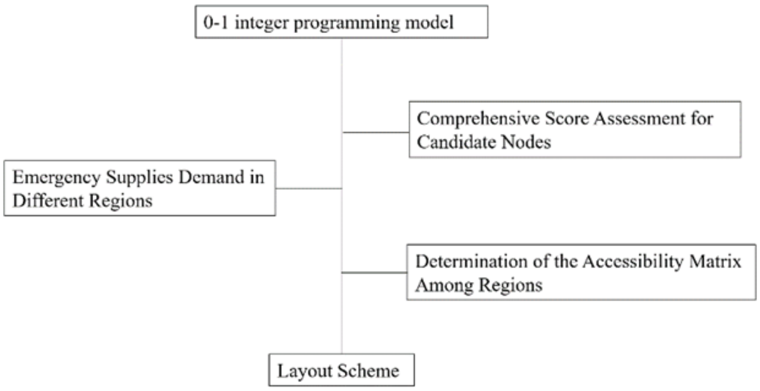


Fig. 1 Steps in solving the site selection model

4.1 Comprehensive score assessment for candidate nodes

The selection process for emergency supply reserve nodes encompasses a broad spectrum of elements, where the judicious choice of evaluation metrics is paramount for the efficient operation, maintenance, and distribution of resources within the warehouses. This paper, considering the specific circumstances of the research locale and drawing upon the *Standards for Emergency Supply Reserve Construction* and the *Specifications for Emergency Logistics Warehousing Facility and Equipment Configuration*, undertakes a holistic assessment of potential nodes. This evaluation spans four critical dimensions: economic considerations, transportation logistics, demographic factors, and the standard of medical services. Employing the Entropy Weight Method enables the calculation of the relative weights of these indicators, which in turn facilitates the aggregation of comprehensive scores for each prospective node.

Table 2 Evaluation indicator system

Target layer	Index layer		Weight
Comprehensive Evaluation Indicator System for Candidate Nodes	Economic Index	PERGDP	0.3252
	Transportation Index	Highway Mileage	0.1486
	Demographic Index	Year-end Population	0.2370
	Medical Services	Number of Beds in Medical and Health Institutions	0.2532

Table 3 Comprehensive evaluation score of the nodes to be selected

District	Synthesis score	District	Synthesis score	District	Synthesis score
Xingning District	0.2943	Gongcheng Yao Autonomous Region	0.1463	Napo Conty	0.0932
Qingxiu District	0.5994	Lipu	0.1535	Lingyun Conty	0.0958
Jiangnan District	0.2853	Wanxiu District	0.2053	Leye Conty	0.0961
Xixiangtang District	0.5138	Changzhou District	0.1804	Tianlin Conty	0.1458
Liangqing District	0.2137	Longxu District	0.1210	Xilin Conty	0.0710
Yongning District	0.1508	Cangwu Conty	0.1195	Longlin Ethnic Autonomous Region	0.1738
Wuning District	0.3152	Teng Conty	0.3361	Jingxi	0.2197
Longan Conty	0.1462	Mengshan Conty	0.1014	Pingguo	0.2178
Malin Conty	0.1502	CenXi	0.3115	Babu District	0.2359
Shanglin Conty	0.1336	Haicheng District	0.2887	Pinggui District	0.1394
Binyang Conty	0.2834	Yinhai District	0.1277	Zhaoping Conty	0.1406
Heng Conty	0.3523	Tieshangang District	0.3196	Zhongshan Conty	0.1356
Chengzhong District	0.3587	Hepu Conty	0.3726	Fuchua Yao Autonomous Region	0.1112
Yufeng District	0.3352	Gangkou District	0.3594	Jinchengjiang District	0.2107
Liunan District	0.3155	Fangcheng District	0.1649	Yizhou District	0.2555
Liubei District	0.2829	Shangsi Conty	0.1307	Nandan Conty	0.1476
Liujiang District	0.2098	Dongxing	0.0988	Tiane Conty	0.1260
Liucheng Conty	0.1910	Qinnan District	0.2116	Fengshan Conty	0.0590
Luzhai Conty	0.2019	Qinbei District	0.2748	Donglan Conty	0.1072
Rongan Conty	0.1334	Lingshan Conty	0.4366	Luocheng Mulao Autonomous Region	0.1047
Rongshui Miao Autonomous Region	0.2000	Pubei Conty	0.2869	Huangjiang Maonan Autonomous Region	0.1148
Sanjiang Dong Autonomous Region	0.1273	Gangbei District	0.2657	Bama Yao Autonomous Region	0.0924
Xiufeng District	0.1382	Gangnan District	0.1701	Duan Yao Autonomous Region	0.1974
Diecai District	0.0942	Qintang District	0.1828	Dahua Yao Autonomous Region	0.1535
Xiangshan District	0.2013	Pingnan Conty	0.4126	Xingbin District	0.3818
Qixing District	0.1465	Guiping	0.5473	Xincheng Conty	0.1358
Yanshan District	0.0309	Yuzhou District	0.3260	Xiangzhou Conty	0.1500
Lingui District	0.2025	Fumian District	0.1073	Wuxuan Conty	0.1542
Yangshuo Conty	0.1341	Rong Conty	0.2438	Jinxiu Yao Autonomous Region	0.0865
Lingchuan Conty	0.1631	Luchuan Conty	0.2935	Heshan	0.0444
Quanzhou Conty	0.2708	Bobai Conty	0.4785	Jiangzhou District	0.1923
Xingan Conty	0.1804	Xingye Conty	0.1931	Fusui Conty	0.1887
Yongfu Conty	0.1366	Beiliu	0.3996	Ningming Conty	0.1684
Guangyang Conty	0.1088	Youijang District	0.3131	Longzhou Conty	0.1442
Longsheng Ethnic Autonomous Region	0.1021	Tianyang District	0.1800	Daxin Conty	0.1440
Ziyuan Conty	0.0978	Tiandong Conty	0.2021	Tiandeng Conty	0.1245
Pingle Conty	0.1553	Debao Conty	0.1485	Pingxiang	0.1004

Based on the comprehensive evaluation scores of the nodes, the line-filling diagram is shown in Fig. 2, and the corresponding data are provided in Tables 2 and 3. It can be intuitively observed from Fig. 2 that there are differences in the comprehensive evaluation scores of each node, which can assist the government in quickly and scientifically selecting sites for the operation, maintenance, and material transportation of the storage pool.

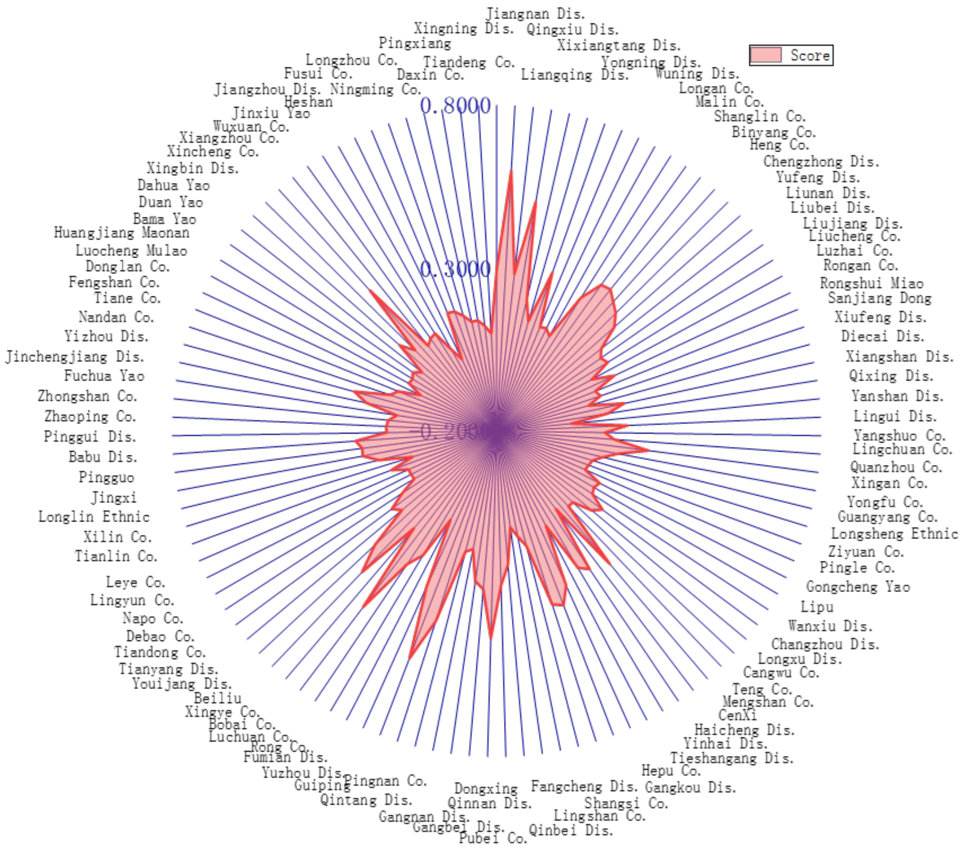


Fig. 2 Score distribution of the comprehensive evaluation score of the nodes to be selected

4.2 Analysis of emergency supplies demand in different regions

Currently, in practical operations, the prediction of emergency supplies demand primarily relies on expert judgment, and there is a noticeable absence of sophisticated forecasting methodologies. Moreover, coupled with the inherent unpredictability of nature disasters, substantially elevates the complexity involved in conducting research on demand forecasting for emergency supplies. Nevertheless, a fundamental principle followed in forecasting the demand for emergency supplies is to analyse the average quantity of supplies needed under different disaster levels based on historical statistical data. this paper adopts the emergency supplies demand model used by scholar Xiaoguang Guo. The model is delineated as follows:

$$q = \alpha \cdot X \tag{25}$$

$$X = X_{min} + r \cdot (X_{max} - X_{min}) \tag{26}$$

In these equations, q signifies the requisite quantity of basic supplies per individual affected by the disaster, α denotes the demand for basic supplies per individual during the critical rescue period, and X represents the displaced population in various regions. X_{max} is the peak historical displaced population recorded during the most severe disaster scenarios, X_{min} is the nadiral historical displaced population recorded during the least severe disaster scenarios, r stands for the normalized risk value across different region. The specific value of α is provided in the Table 4.

The supply demand for each region, calculated using the above data and formulas, is shown in Table 5.

Table 4 Emergency supplies demand during golden rescue period

Description	Foodstuffs	Drinking water	Tent	Cotton quilt	Medical supplies
Quantity	0.5kg/day	1.5L/day	1 /3 persons	1 set	1 set
Weight	1.5 kg	4.5 kg	16.7 kg	3 kg	4 kg

Table 5 Demand for materials

District	Displaced population	Individual supplies (kg)	Regional supplies (kg)
Xingnin District	6	29.7	164.92
Qingxiu District	119	29.7	3522.73
Jiangnan District	26	29.7	775.18
Xixiangtang District	4	29.7	113.28
Liangqing District	702	29.7	20839.99
Yongning District	502	29.7	14904.61
Wuming District	8	29.7	245.74
Longan Conty	6	29.7	168.01
Mashan Conty	15	29.7	436.24
Shanglin Conty	8	29.7	232.52
Binyang Conty	59	29.7	1747.27
Heng Conty	37	29.7	1099.48
Chengzhong District	505	29.7	14992.84
...	...	...	...
...	...	...	...
Ningming Conty	3101	29.7	92109.18
Longzhou Conty	1259	29.7	37387.10
Daxin Conty	89	29.7	2634.69
Tiandneg Conty	71	29.7	2121.85
Pingxiang	315	29.7	9348.28

4.3 Determination of the accessibility matrix among regions

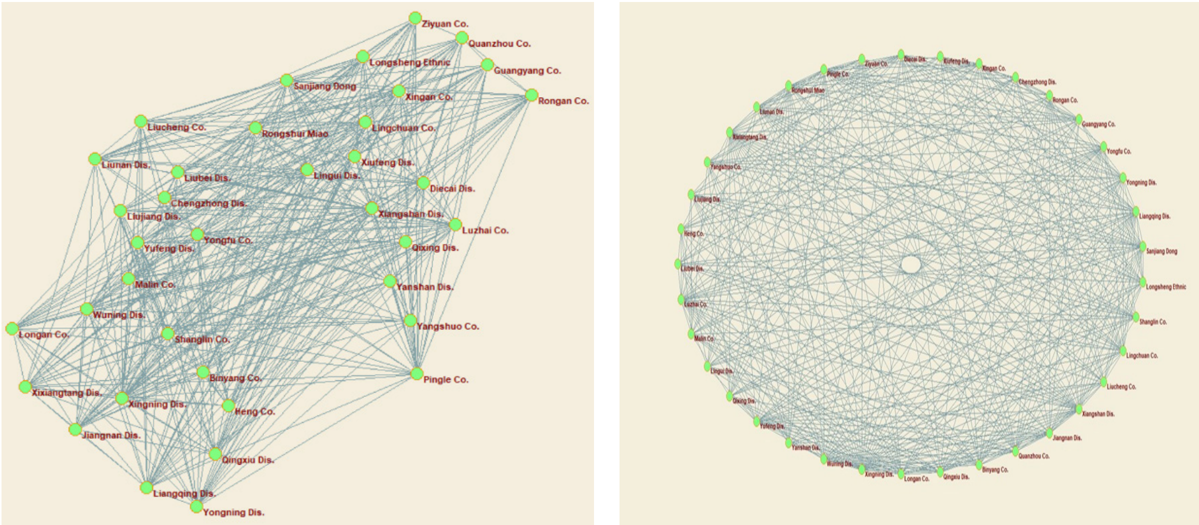
Calculate the distances between regions and determine their accessibility based on the first emergency response time criterion (6 hours). The accessibility matrix is presented in Table 6.

Table 6 Regional accessibility matrix

District	Xingning district	Qingxiu district	Jiangnan district	Xixiangtang district	Liangqing district	Yongning district	...	Longan conty	Mashan conty	Shanglin conty
Xingning District	1	1	1	1	1	1	...	1	1	1
Qingxiu District	1	1	1	1	1	1	...	1	1	1
Jiangnna District	1	1	1	1	1	1	...	1	1	1
Xixiangtang District	1	1	1	1	1	1	...	...	...	...
Liangqing District	1	1	1	1	1	1	...	...	...	...
Yongniang District	1	1	1	1	1	1	...	...	...	...
...	...	...	...	...	...	...	1	...	...	...
...	...	...	...	...	...	...	...	...	...	...
Longan Conty	1	1	1	...	...	...	...	1	...	...
Mashan Conty	1	1	1	...	...	...	...	...	1	...
Shanglin Conty	1	1	1	...	...	...	...	...	...	1

According to the data of Table 6 to draw the networks diagram of Fig. 3, which Fig. 3a is the network diagram of relative geographical location reachable, and Fig. 3b is the network diagram of random location reachable. According to the connections in Fig. 3, it can be easily checked whether each region can carry out emergency measures, such as the allocation of materials and personnel transfer, within the initial emergency rescue time.

During a disaster, if roads are blocked or infrastructure is damaged, these logistics disruptions can significantly affect the rescue time and routes. Specifically, these factors will alter the critical paths in the accessibility matrix, thereby influencing the allocation of rescue time. For instance, areas that could originally be reached via an efficient route may be forced to adopt more detours or longer paths due to infrastructure damage, thereby prolonging the rescue time.



a) b)

Fig. 3 a) Map of geographically accessible networks; b) Map of regional accessible networks

In the model calculation, the presence of these logistics' interference factors will increase the uncertainty of the rescue time. Although the model has considered the time limit for rescue response, these factors may further exacerbate the inaccuracy of the predictions. Moreover, as can be seen from Fig. 3, the logistics relationships between different regions are not unique. In the event of a disaster in a certain area, rescue services can be provided through multiple paths or various allocation methods. This diversity provides greater flexibility for emergency response and a wider range of response strategies. In this study, only the single path from location A to location B was considered. In fact, to avoid the emergency response issues caused by road damage, decision regarding path selection need to be made at different nodes to achieve the goal of minizine time and cost [31].

4.4 Model solution

The problem was solved using LINGO (Linear Interactive and General Optimizer) software from Lindo System Inc. in the United States. This software can be used to solve nonlinear programming problems, as well as some linear and nonlinear equation systems.

In this paper, when the risk level in the area is higher than 4, a level 1 reserve station can be established; when the risk level is the area is higher than 3 but lower than 4, a level 2 reserve station can be established; when the risk level is the area is between 3 and 1, a level 3 reserve station can be established; and when the risk level is lower than 1, a reserve station may not necessary. The code is as follows.

```
Sets:
ii /1..111/: zi1, zi2, zi3;
ENDSETS

DATA:
zi1 = @ole('d:\data2.xlsx', 'zi1_');
zi2 = @ole('d:\data2.xlsx', 'zi2_');
zi3 = @ole('d:\data2.xlsx', 'zi3_');
ENDDATA

zi1sum = @sum(ii(i): zi1(i))/3;
zi2sum = @sum(ii(i): zi2(i))/2;
zi3sum = @sum(ii(i): zi3(i));
```

A total of 58 third-level stations, 8 second-level stations, and 2 first-level stations are required. The solution is shown in Figs. 4 and 5.

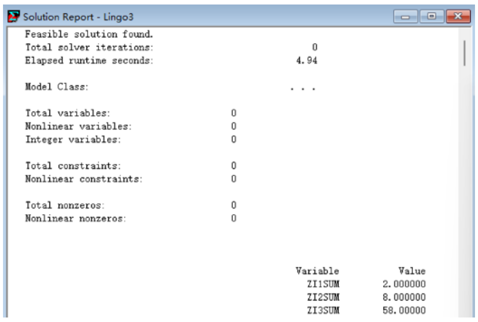


Fig. 4 The result of solving the number of reserve stations using Lingo

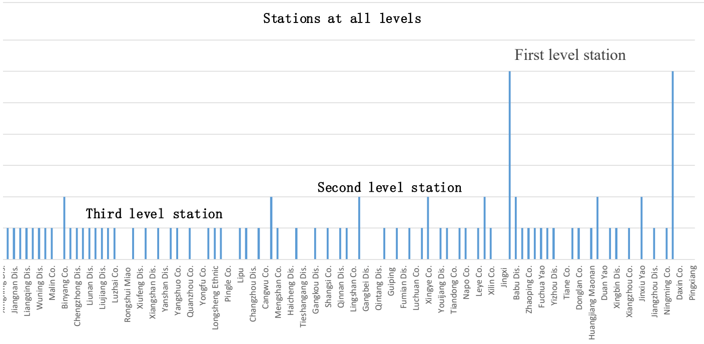


Fig. 5 Distribution of Stations at All Levels

The program code for calculating the distribution of materials in each region is as following:

```
SETS:
ii /1..111/ : zi1, zi2, zi3, fi, ri;
jj /1..111/ : wj;
kk /1..3/   : ck, ak;
linkij(ii,jj): tij, wij;
ENDSETS
```

zi1, zi2, zi3 are the first-, second-, and third-level emergency material reserves, respectively, with a value of 1 if established and 0 otherwise; fi is the comprehensive evaluation score of the node; ri is the risk factor; wj is the economic factor; ck is the construction cost of the storage station; and ak is the availability of first-, second-, and third-level materials. The necessary values are then entered into the collection array.

```
DATA:
ck = 10860000 6280000 1350000;
ak = 730000 210000 26000;
f1 = 0.175;
f2 = 0.256;
r1 = 4;
r2 = 3;
fi  = @ole('D:\data2data.xlsx','fj');
ri  = @ole('D:\data2data.xlsx','rj');
wj  = @ole('D:\data2data.xlsx','wj');
tij = @ole('D:\data2data.xlsx','tij');
ENDDATA
```

Next, define the objective functions and constraint conditions.

```
MIN = @SUM(ii(i): (ck(1)*zi1(i))/fi(i) + (ck(2)*zi2(i))/fi(i) + (ck(3)*zi3(i))/fi(i));
@FOR(ii(i): m*(zi1(i) + zi2(i) + zi3(i)) - @SUM(jj(j): wij(i,j)) >= 0);
@FOR(ii(i): @SUM(jj(j): wij(i,j)) <= ak(1)*zi1(i) + ak(2)*zi2(i) + ak(3)*zi3(i));
```

Finally, solve the model. Input the model parameters and relevant data into Lingo for solving, and the optimal state and quantity of emergency materials reserve at all levels were obtained. The solution results are in Table 7, which can meet the material demand of accessible areas. Among these, the total quantity of materials that can be supplied by all reserve stations is 4648000 kg, and the minimum construction cost is 15026 million yuan.

Table 7 Solution of the model

District	The total amount of materials that can be provided	Cost	District	The total amount of materials that can be provided	Cost
Xingning Dis.	26000	1350000	Yinhai Dis.	26000	1350000
Qingxiu Dis.	26000	1350000	Gangkou Dis.	26000	1350000
Jiangnan Dis.	26000	1350000	Shangsi Co.	26000	1350000
Xixiangtang Dis.	26000	1350000	Qinnan Dis.	26000	1350000
Liangqing Dis.	26000	1350000	Qinbei Dis.	26000	1350000
Yongning Dis.	26000	1350000	Pingnan Co.	26000	1350000
Wuning Dis.	26000	1350000	Yuzhou Dis.	26000	1350000
Longan Co.	26000	1350000	Rong Co.	26000	1350000
Malin Co.	26000	1350000	Bobai Co.	26000	1350000
Chengzhong Dis.	26000	1350000	Youijang Dis.	26000	1350000
Yufeng Dis.	26000	1350000	Tianyang Dis.	26000	1350000
Liunan Dis.	26000	1350000	Debao Co.	26000	1350000
Liubei Dis.	26000	1350000	Napo Co.	26000	1350000
Liujiang Dis.	26000	1350000	Leye Co.	26000	1350000
Liucheng Co.	26000	1350000	Xilin Co.	26000	1350000
Luzhai Co.	26000	1350000	Pinggui Dis.	26000	1350000
Sanjiang Dong	26000	1350000	Zhaoping Co.	26000	1350000
Diecai Dis.	26000	1350000	Zhongshan Co.	26000	1350000
Qixing Dis.	26000	1350000	Fuchua Yao	26000	1350000
Lingui Dis.	26000	1350000	Jinchengjiang Dis.	26000	1350000
Yangshuo Co.	26000	1350000	Yizhou Dis.	26000	1350000
Quanzhou Co.	26000	1350000	Fengshan Co.	26000	1350000
Guangyang Co.	26000	1350000	Donglan Co.	26000	1350000
Longsheng Ethnic	26000	1350000	Huangjiang Maonan	26000	1350000
Ziyuan Co.	26000	1350000	Dahua Yao	26000	1350000
Lipu	26000	1350000	Xingbin Dis.	26000	1350000

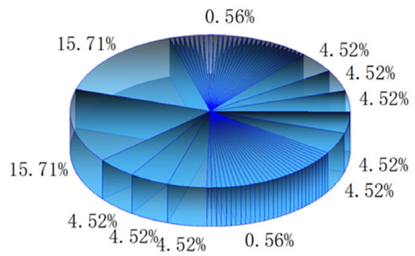


Fig. 6 Proportion of materials distribution by region

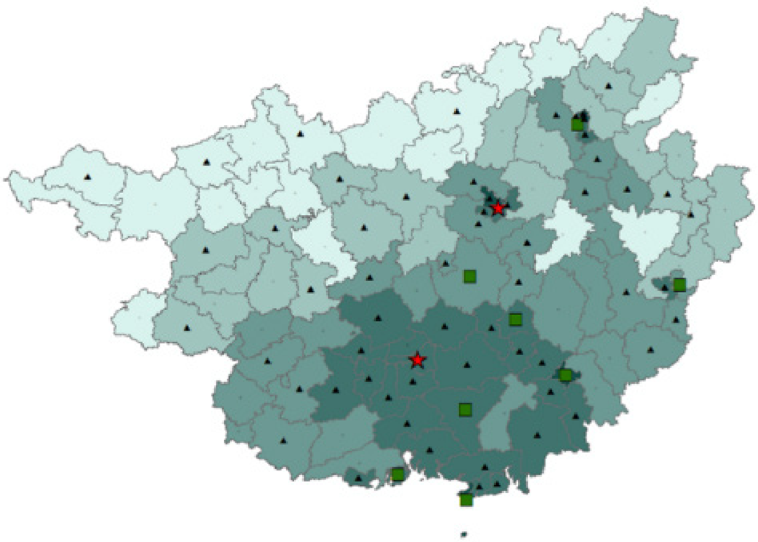


Fig. 7 Optimization diagram of the emergency material reserve repositories layout in Guangxi

5. Results and discussion

Considering the risks posed by natural disasters, this study integrates temporal and economic considervations to optimize the site selection and layout of emergency materials storage facilities, as shown in Figs. 6 and 7. The simulation result reveal that the proposed optimization strategy offers the benefits of low cost while ensuring timely emergency response coverage across the entire region. The key characteristics and advantages of the optimized site selection and layout are outlined as follows.

Initially, efficient regional coverage without high costs. This study introduces a hierarchical site selection framework for emergency material reserves that spans provincial, civic, and county levels, facilitating efficient regional coverage without incurring prohibitive costs. By integrating comprehensive analyses of emergency materials demands across the region, our framework significantly reduces the requisite number of storage facilities. Drawing upon the directives of the 14th Five-Year Plan for Emergency Materials Support of Guangxi, which advocates for the establishment of emergency material reserves at all city and county levels—including the construction of at least one first-level reserve, 14 second-level reserves, and 96 third-level reserves—our optimized layout suggests a feasible reduction of 6 second-level reserves and 38 third-level reserves. This reduction is achieved without compromising the serviceability of the emergency materials support system. Specifically, our approach proposes a cost-effective reserve system organized into provincial-level (first-level), municipal-level (second-level), and county-level (third -level) reserves, thereby optimizing both the spatial distribution and construction cost of emergency material storage facilities.

Subsequently, strategic reserve allocation in high-risk areas. This study addresses the imperative of enhancing emergency supplies within high-risk zones through strategic reserve allocation. By conducting a detailed risk assessment of natural disasters, the study meticulously identifies areas of elevated risk and advocates for the establishment of high-tier reserve banks specifically tailored to these locales. It underscores the necessity of tailoring the creation of reserve banks to the real-world conditions of the proposed sites, predicated on a thorough evaluation of each area's specific needs and vulnerabilities, as shown in Fig. 8. The findings reveal that all high-tier reserve banks are strategically situated in regions with a risk rating of third level or higher, ensuring their alignment with areas of greatest need. Notably, two significant provincial emergency supply reserves have been established in Qingxiu District of Nanning and Chengzhong District of Liuzhou. Both districts are recognized as high-risk and high-priority areas, underscoring the strategic alignment of site selection and layout with existing planning frameworks and policy mandates. This approach not only enhances the efficacy of emergency preparedness but also aligns with broader strategic objectives to mitigate the impact of natural disasters in high-risk areas.

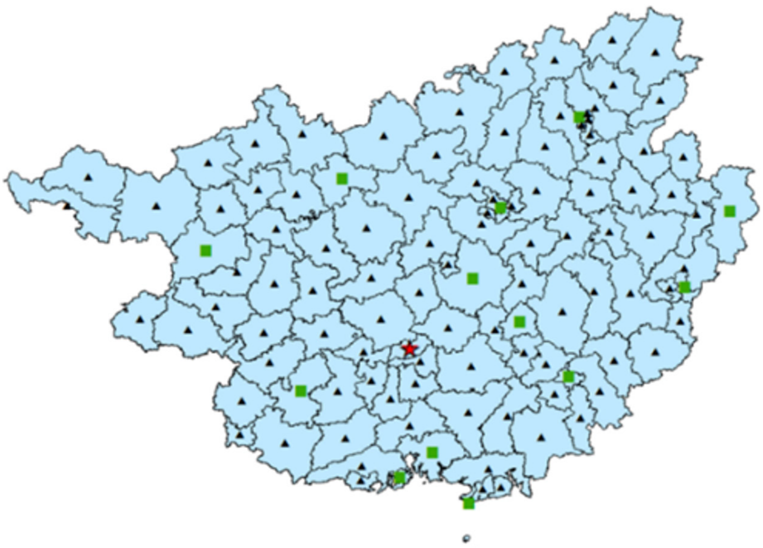


Fig. 8 Current situation of emergency material reserve repositories

Moreover, cross-regional distribution and coordinated layout. The optimized emergency supplies reserve system presented in this paper is meticulously designed to meet the emergency material needs of the region it serves, while also offering logistical support to adjacent areas. This system includes a high-grade reserve capable of providing material support to other regions within the city, embodying a cross-regional distribution strategy, as shown in Fig. 9. This approach ensures a comprehensive and coordinated emergency preparedness framework, markedly improving the emergency supplies network's responsiveness and coordination. The strategic implementation of this system underscores the importance of a holistic view in emergency management, facilitating a seamless flow of resources across regional boundaries. By doing so, it addresses both localized and wider-scale emergency situations, significantly enhancing the efficacy and reach of emergency response efforts.

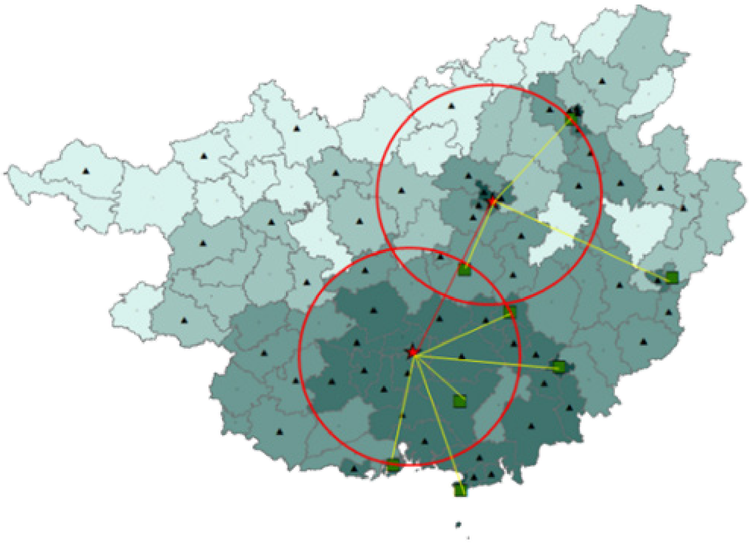


Fig. 9 Results of optimal layout of provincial-municipal-county emergency material reserve repositories

6. Conclusion

This research leverages foundational principles and strategic objectives of site selection to undertake a comprehensive analysis encompassing site selection costs, materials distribution timing, and regional disaster risk assessments. Following this, we develop a multi-level coverage location model, meticulously crafted to align with predefined optimization objectives and pertinent constraints. An algorithm specifically designed for this model facilitates the resolution of the complex site selection problem, leading to the identification of an optimal layout. These optimal layout findings are then rigorously examined through both qualitative and quantitative analyses, ensuring a robust and comprehensive evaluation of the site selection strategy. This methodological approach not only optimizes resource allocation and emergency response efficiency but also contributes significantly to the existing body of knowledge by introducing a novel, scalable solution for emergency supplies logistics and disaster risk management.

To be more specific, first, this paper introduced a nuanced, graded site selection system specifically designed for the strategic placement of emergency materials reserve facilities. The primary aim of this system is to minimize the costs associated with managing emergencies. We identify a notable disparity in certain regions between the frequency of natural disasters and the level of regional economic development. In response, we recommend the establishment of a three-tiered emergency materials reserve system, encompassing provincial, city, and county levels. This strategic approach optimizes the allocation of large storage facilities while advocating for a reduction in the number of smaller ones. Such optimization not only curtails resource wastage but also significantly enhances the accessibility of emergency materials at the county level, thereby elevating the overall efficiency of emergency rescue operations. This methodology is poised to offer a robust framework for improving disaster preparedness and response strategies, particularly in areas where economic development does not necessarily correlate with disaster vulnerability.

Secondly, this study proposes a collaborative strategy that aligns with key regulatory frameworks, including the *National emergency plan for Natural disaster relief* and the *Guiding opinion on strengthening the reserve system for natural disaster relief materials*. These documents underscore the necessity for establishing robust emergency material reserves. There is an approach that partnerships with relevant enterprises can be forged. This collaboration is designed to integrate material reserves with existing production capacities, enhancing the overall efficacy and capacity of the reserves system. By leveraging the strengths of both public emergency planning and private production capabilities, this strategy aims to create a more resilient and responsive emergency materials reserve system. Such integration not only adheres to the regulatory mandates but also amplifies the comprehensive capacity to respond to natural disasters, thereby contributing significantly to the enhancement of national disaster preparedness and relief efforts.

Thirdly, enhancing the coordination within the overarching framework is crucial for the effective implementation of a multi-tiered layout strategy for emergency material reserves. This study underscores the importance of fostering cross-regional collaboration in the management of emergency materials. Such collaboration aims to augment the adaptability of regional temporary material reserves during emergency situations. This approach not only addresses and coordinates potential deficiencies in material supplies but also significantly enhances our collective resilience to global risks. By integrating cross-regional cooperation into the strategic layout, the proposed model advances a more dynamic and responsive emergency management system. This enhanced model of emergency material management thus contributes to a robust infrastructure capable of mitigating the impact of disasters through improved preparedness and response mechanisms.

This present study introduced a pioneering model designed for emergency material storage warehouses, characterized by its focus on a single cycle and a single material type. This model represents a foundational step towards optimizing the site selection process for emergency material reserves. Recognizing the model's current limitations, we identify a significant avenue for future research: the expansion of this model to accommodate multiple stages and material types. Such an evolution would not only enhance the model's precision and adaptability but also significantly increase its scientific rigor. By integrating a broader spectrum of variables and complexities into the model, future iterations could offer more nuanced insights into the logistics of emergency material storage and distribution. This progression promises to refine the strategic planning of emergency material reserves, ultimately contributing to more effective disaster response and management.

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