Optimization of Flood Emergency Evacuation Strategies Based on GIS and Multi-Criteria Decision Analysis

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Abstract: The efficiency and safety of emergency evacuation directly concern people's lives under extreme floods. Taking the upper Ying River Basin as the study area, evacuation zoning was carried out based on graded flood susceptibility, and a workflow of “candidate area screening – spatial optimization – safety constraints” was constructed to extract candidate shelter areas. A multi-criteria evaluation system comprising safety, distance, accessibility and capacity was weighted by AHP (safety 0.41, accessibility 0.27, distance 0.18, capacity 0.14; CR = 0.022) for quantitative shelter optimization, and three path models were comparatively analysed. The optimized shelters are characterized by “low-risk orientation, clustering along roads and multi-point distribution”; the shortest path is efficient but crosses medium-to-high risk zones in places; the raster cost path avoids risks but lacks origin–destination matching; while the risk-weighted road network model avoids high-risk zones while guaranteeing accessibility, achieving a dynamic balance between risk and efficiency. The findings provide methodological support for flood emergency evacuation planning.

Keywords: Emergency evacuation; Shelter site selection; Multi-criteria decision analysis; Route optimization; GIS

1. Introduction

Floods are characterized by sudden onset, rapid development and complex disaster chains. Once an extraordinary flood occurs, emergency evacuation of threatened residents is the key measure to reduce casualties [8]. Evacuation involves the complete chain of “transfer demand identification – shelter site selection – route planning” and is a typical multi-criterion, multi-objective spatial decision problem: routes should be short and avoid high-risk zones, and shelters should be safe, accessible and capable.

Abundant results have been achieved in evacuation route optimization, including shortest-path algorithms [1], multi-objective optimization models [4,7], evolutionary algorithms [5] and location–routing joint optimization [6]; for shelter selection, combining multi-criteria decision analysis with GIS is the mainstream approach [9]. However, most studies treat site selection and route planning separately, and few explicitly incorporate flood risk into the whole process of “zoning – selection – routing”, especially the risk–efficiency trade-off in route optimization [2-3].

Based on the graded susceptibility results, this study systematically carries out evacuation zoning, shelter optimization and route optimization, and compares three path models to balance safety and efficiency.

2. Evacuation Zoning and Shelter Site Selection

2.1 Zoning Basis

The evacuation zoning is based on four aspects: (1) the graded susceptibility results — highly susceptible zones are prone to ponding, overflow or traffic interruption and thus have high evacuation urgency, whereas low-susceptibility zones are suitable as shelter areas; (2) settlement distribution — concentrated settlements generate higher demands; (3) road conditions — accessible areas can serve as main evacuation corridors, while poorly connected or flood-prone areas require higher priority; (4) shelter demand — both "areas to be evacuated" and "areas available for sheltering" should be incorporated into a unified framework.

2.2 Candidate Shelter Area Extraction

Candidate shelter areas were determined with flood safety as the prerequisite. The low and medium-low susceptibility zones were extracted in ArcGIS as initial candidates; spatial optimization then removed small patches and merged same-class polygons to eliminate scattered patches (Figure 1).

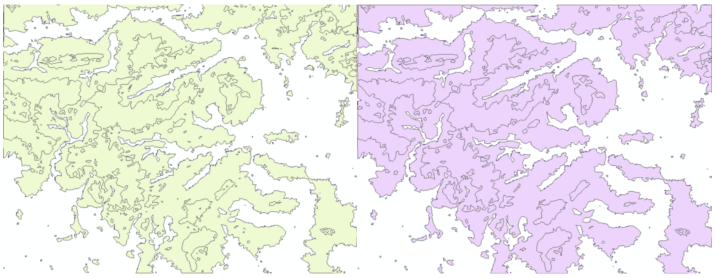

Figure 1: Candidate shelter areas before (left) and after (right) optimization.

Since settlements are regarded as potentially affected areas with high surrounding risk, an 800 m settlement buffer was erased from the candidate areas to maintain a safety distance (Figure 2); finally, the road network was overlaid to remove areas far from roads. Through these constraints, the candidate shelter areas and corresponding site set were constructed.

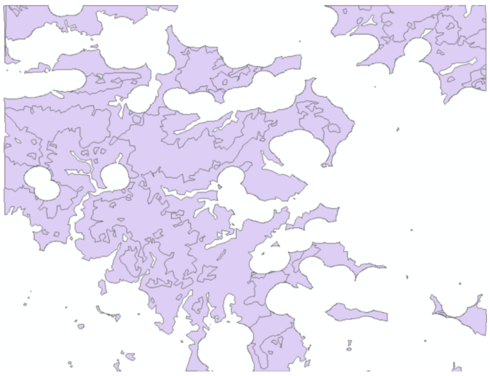

Figure 2: Candidate shelter areas after erasing the 800 m settlement buffer.

2.3 Multi-Criteria Evaluation and Shelter Optimization

An evaluation system comprising safety, distance, accessibility and capacity was constructed: safety (S) takes the susceptibility grade with reverse scoring; distance (D) is the distance to the nearest settlement; accessibility (A) is the distance to the nearest road; capacity (C) counts the available area within a buffer around the site. Min–max standardization was applied:

$$X' = (x - x_{min})/(x_{max} - x_{min}) \tag{1}$$

$$X' = (x_{max} - x)/(x_{max} - x_{min}) \tag{2}$$

where Equation (1) applies to positive and Equation (2) to negative indicators. The AHP weights were determined [9] by a judgment matrix following the principle of "safety first, considering transfer efficiency and carrying capacity"; the consistency ratio CR = 0.022 < 0.1 indicates reliable weights: safety 0.41, accessibility 0.27, distance 0.18 and capacity 0.14 (Table 1).

Table 1: Weights of shelter evaluation indicators.

Indicator	Weight
Safety (S)	0.41
Accessibility (A)	0.27
Distance (D)	0.18
Capacity (C)	0.14

A linear weighted comprehensive evaluation model was constructed:

$$S = \sum W_i X_i \tag{3}$$

Candidate sites were ranked by comprehensive scores; high-scoring sites were selected as optimal shelters with some sub-optimal sites retained (Figure 3). The optimal shelters are mainly in low-susceptibility zones and basically avoid high-susceptibility areas; they are distributed in belts along main roads with local clustering at junctions, and lie outside settlements with a certain distance, verifying the buffer constraint. Overall, the layout is characterized by "low-risk orientation, clustering along roads and multi-point distribution".

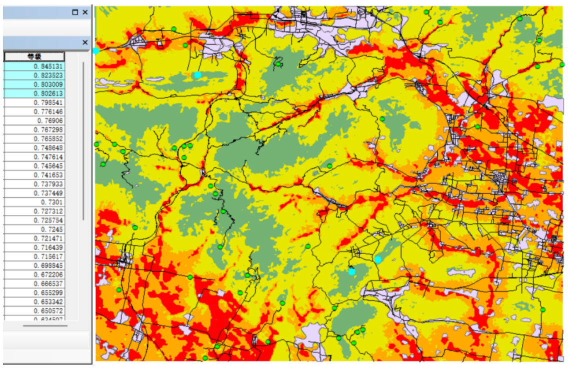

Figure 3: Spatial distribution of optimized shelter sites.

3. Evacuation Route Optimization

3.1 Shortest Path Analysis on the Road Network

Taking settlements as origins, optimized shelters as destinations and the road network as the carrier, an "origin–route–destination" framework was constructed. After topological checking, the ArcGIS network analysis module [10] computed the shortest path [1] from each settlement to its nearest shelter with road length as impedance. The paths follow the road network with a clear structure, but some cross medium-to-high risk zones, because the model only minimizes distance and neglects flood risk, posing safety hazards in actual evacuation (Figure 4).

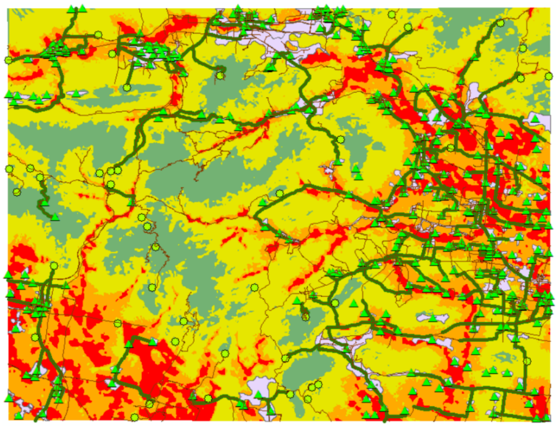

Figure 4: Shortest path results based on the road network.

3.2 Raster Cost Path Model with Flood Risk

To improve route safety, a flood risk constraint was introduced to construct a cost-distance-based model. Letting R denote the risk grade, the cell traversal cost is

$$C = (1 + \alpha R) \tag{4}$$

where α is the risk weight coefficient; a discretized cost surface was built by assigning differentiated costs to risk grades, and the objective is the minimum cumulative cost:

$$\min Z = \sum c_i d_i \tag{5}$$

where c_i is the cost of cell i and d_i its length. The paths generally avoid high-risk zones; however, some paths converge conspicuously without directly connecting the corresponding shelters — the cost path model performs global optimization by minimum cumulative cost without one-to-one origin–destination matching, which is limited in multi-source multi-target scenarios (Figure 5).

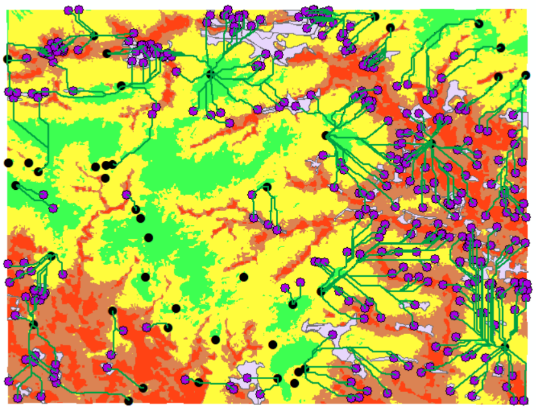

Figure 5: Cost path analysis results.

3.3 Risk-Weighted Road Network Path Model

The two models above have advantages in efficiency and risk avoidance respectively, but the former neglects flood risk and the latter lacks network constraints. Therefore, the susceptibility grades were overlaid with the road network to assign risk attributes to each road, and a comprehensive cost function was constructed:

$$C_i = L_i(1 + \beta R_i) \tag{6}$$

where Ci is the cost of road i, Li its length, Ri its flood risk grade and β the risk adjustment coefficient. With the comprehensive cost as impedance, the minimum cost path from each settlement to its optimal shelter was computed, realizing route optimization under multi-source multi-target conditions.

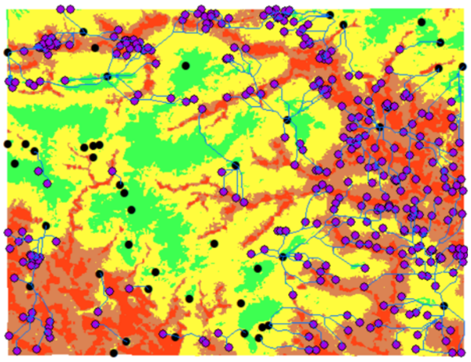

Figure 6: Route optimization results of the risk-weighted road network model.

3.4 Comparative Analysis

The optimized routes show a clear safety-oriented pattern: most routes follow the road network and avoid high-risk zones overall; compared with the shortest path results, they make obvious detours along the edges of very high-risk zones and prefer medium-low risk areas, shifting the mechanism from "single distance optimality" to "comprehensive risk–distance optimality". In road-limited areas a few routes still cross high-risk zones due to the lack of alternatives, reflecting the constraint of the real traffic network.

In terms of overall structure, all settlements are effectively connected with shelters, and the route distribution is balanced without abnormal convergence or breakage, indicating good stability for multi-source multi-target analysis; routes strictly follow the road network, ensuring operational feasibility. In summary, the risk-weighted road network model balances safety and accessibility and embodies the shift from efficiency orientation to safety priority under disaster scenarios.

4. Conclusions

Based on the graded flood susceptibility results, this study systematically carried out evacuation zoning, shelter optimization and route optimization. The main conclusions are: (1) the "screening – optimization – constraints" workflow effectively extracted candidate shelter areas, and the four-indicator AHP model (CR = 0.022) yields shelters characterized by "low-risk orientation, clustering along roads and multi-point distribution"; (2) the three path models have their own strengths and weaknesses — the shortest path model is efficient but neglects risk, the raster cost path avoids risk but lacks network constraints and origin–destination matching, and the risk-weighted road network model balances safety and accessibility with the best overall performance; (3) the risk-weighted model reveals the regulating effect of flood risk on route decision-making, providing methodological support for evacuation planning. Future research can combine dynamic flood routing and road capacity for time-varying evacuation simulation.

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