

Evaluation of the Disaster Resilience Efficiency of the Central Plains Urban Agglomeration's Transportation Infrastructure under the Scenarios of External Flood and Internal Waterlogging

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Abstract: As a national comprehensive transportation hub, the Central Plains Urban Agglomeration faces dual threats of external flooding and internal waterlogging, making it imperative to enhance the disaster resilience of its transportation infrastructure. Addressing the limitations of existing research in adaptability and the absence of systematic evaluation at the urban agglomeration level, this study employs the DEA-BCC model based on resilience theory to construct an efficiency evaluation system for transportation infrastructure resilience. The core concepts of resilience are defined, and three categories of input indicators (engineering hardware, management softness, and spatial ecology) along with corresponding output indicators for resilience dimensions are designed following the principles of scientific rigor, comparability, and practicality. The application logic of the model in identifying efficiency patterns, projection optimization analysis, and regional coordination reference is elucidated. The study demonstrates that the DEA-BCC model objectively identifies disparities in resilience construction efficiency among cities and provides quantifiable optimization pathways for underperforming cities. This evaluation framework offers scientific support for formulating differentiated strategies for transportation resilience development in the Central Plains Urban Agglomeration and serves as a reference for similar regions. Future research could integrate panel data and regression models to further investigate the dynamic evolution and influencing factors of resilience efficiency.

Keywords: External Flooding and Internal Waterlogging; Central Plains Urban Agglomeration; Transportation Infrastructure; Disaster Resilience; DEA-BCC Model; Efficiency Evaluation.

1. Introduction

Driven by global climate change and rapid urbanization, extreme flooding events have become increasingly frequent, posing serious threats to the safe operation of urban transportation infrastructure. As the strategic core of national regional economic development and a comprehensive transportation hub, the Central Plains Urban Agglomeration—home to a dense population, concentrated industries, and critical infrastructure—faces dual risks of external flood backflow and internal waterlogging. The catastrophic "7·20" heavy rain disaster in Zhengzhou in 2021 starkly exposed the region's transportation system's vulnerability to extreme disasters (Song Xiaomeng et al., 2024). As the "lifeline" of cities, transportation infrastructure's disaster resilience directly impacts emergency evacuation, relief supply delivery, and essential social operations. Enhancing its resilience has become an urgent priority for implementing China's "Resilient City" development strategy.

Current academic research on resilience theory has established a new paradigm for urban disaster prevention, yet existing studies remain significantly limited. While foreign research has taken the lead in theoretical frameworks and methodologies, its indicator systems and model parameters based on Western urban contexts exhibit compatibility issues with the infrastructure conditions and disaster characteristics of the Central Plains Urban Agglomeration (Bruneau et al., 2003). Domestic studies predominantly focus on static analyses of single-city cases or specific disaster types, lacking systematic resilience efficiency evaluations at the urban

agglomeration level (Liu Xiguang et al., 2025). Data Envelopment Analysis (DEA), as an objective evaluation method that requires no predefined indicator weights, demonstrates unique advantages in multi-input, multi-output efficiency assessments. It is particularly suitable for comparative analysis of resilience levels among cities within the Central Plains Urban Agglomeration (Liu Xiguang et al., 2021). Building on this foundation, this paper focuses on DEA efficiency evaluation methods to construct a disaster-resilient assessment system for transportation infrastructure in the Central Plains Urban Agglomeration under external flood and internal waterlogging scenarios. By introducing standardized BCC model formulas to deepen methodological applications, this study provides theoretical support and methodological references for enhancing regional resilience.

2. Theoretical Basis and Evaluation Methods

2.1. Definition of the Connotation of Disaster Resilience

The concept of "resilience" originates from ecology, where Holling (1973) defined it as a system's capacity to absorb disturbances and maintain core functions. This concept has since been extended to urban disaster prevention. By integrating the flood characteristics of the Central Plains Urban Agglomeration with the functional positioning of transportation infrastructure, this study defines disaster-resilient transportation infrastructure as: a system's comprehensive capability to sustain core transportation functions, rapidly respond to disaster impacts, and achieve

adaptive learning through processes of resistance, absorption, recovery, and adaptation under coupled disturbances of "external flooding and internal waterlogging." Its core dimensions encompass four aspects: resistance, absorption, recovery, and adaptation (Cheng Xiaotao et al., 2022). This definition not only reflects the core principles of resilience theory but also fully considers the unique disaster risk structure of the Central Plains Urban Agglomeration.

2.2. DEA Evaluation Method and BCC Model Construction

Data Envelopment Analysis (DEA), a multi-objective decision-making method based on relative efficiency, offers the key advantage of eliminating subjective weight assignment. Through linear programming, it objectively

$$\min \theta - \varepsilon \left(\sum_{i=1}^m s_i^- + \sum_{r=1}^s s_r^+ \right) \quad s. t. \quad \begin{cases} \sum_{j=1}^n \lambda_j x_{ij} + s_i^- = \theta x_{ik}, & i = 1, 2, \dots, m \\ \sum_{j=1}^n \lambda_j y_{rj} - s_r^+ = y_{rk}, & r = 1, 2, \dots, s \\ \sum_{j=1}^n \lambda_j = 1, \\ \lambda_j \geq 0, s_i^- \geq 0, s_r^+ \geq 0, & j = 1, 2, \dots, n \end{cases} \quad (1)$$

Here, θ denotes the comprehensive technical efficiency value of the decision-making unit, with a range of $(0,1]$. A $\theta=1$ indicates DEA efficiency, meaning the input-output ratio achieves optimal allocation. Conversely, a $\theta < 1$ signifies DEA inefficiency, indicating either input redundancy or output insufficiency. s_i^- represents the input slack variable, s_r^+ denotes the output slack variable, ε is the non-Archimedean infinitesimal, and λ_j is the weight coefficient of the decision-making unit.

In terms of evaluation methodology, the study treats major cities within the Central Plains Urban Agglomeration as Decision-Making Units (DMUs). By establishing a disaster-resilience-oriented input-output indicator system, it calculates each city's comprehensive resilience efficiency. Pure technical efficiency reflects the effectiveness of resource allocation and management in urban transportation resilience development, while scale efficiency demonstrates the alignment between input scale and output level in resilience construction (Su Meng, 2025). Through the projection analysis function of the Data Envelopment Analysis (DEA) model, the study further identifies input redundancy and output insufficiency in inefficient cities, providing precise targets for resilience enhancement.

3. Construction of Disaster Resilience DEA Evaluation Index System

3.1. Principles of Indicator Construction

In constructing the indicator system for the Central Plains Urban Agglomeration disaster resilience assessment, we integrate regional disaster characteristics and data availability while adhering to three fundamental principles: First, scientific rigor – indicators must accurately capture the core dimensions and essential features of transportation infrastructure's disaster resilience (He & Zheng, 2022). Second, comparability – metrics should maintain consistent

measures the relative efficiency of decision-making units, making it particularly suitable for evaluating complex systems with multiple inputs and outputs (Tao Liman et al., 2025). To assess the disaster resilience of transportation infrastructure in the Central Plains Urban Agglomeration, this study adopts the BCC model with variable returns to scale. This model decomposes comprehensive efficiency into pure technical efficiency and scale efficiency, enabling more precise identification of efficiency loss sources.

The BCC model treats cities within the Central Plains urban agglomeration as independent decision-making units (DMUs). Assuming n DMUs, each containing m input indicators and s output indicators, the linear programming model developed from an input-oriented perspective is as follows:

statistical standards and clear physical definitions across cities to support cross-regional comparisons. Third, practical applicability – data sources must be publicly available or obtainable through standardized channels, balancing academic rigor with operational feasibility.

3.2. Definition of the Connotation of Disaster Resilience

The evaluation metrics focus on cities' collective efforts to enhance transportation system resilience, covering three dimensions: engineering infrastructure, management practices, and spatial ecology. Engineering infrastructure investments include annual per-unit-area funding for flood control and drainage facilities, as well as special funds for disaster-resistant reinforcement of transportation infrastructure, reflecting the development of physical disaster resilience (Zhang Mingyu, 2024). Management practices investments encompass annual operational costs for emergency management information platforms and funds for disaster prevention awareness campaigns and drills, demonstrating the supporting role of management systems (Jiang Shuoliang et al., 2022). Spatial ecology investments, such as per capita green space and water area coverage, and the proportion of permeable pavement areas, highlight the role of natural water storage capacity in ensuring resilience (Yang Shilin et al., 2024).

The output indicators focus on measuring the common performance capabilities of transportation systems during flood disasters, corresponding to the core dimensions of resilience: Resistance and Absorption Capacity are measured by indicators such as the average traffic speed retention rate of the main road network during extreme rainfall and the duration of critical transportation hubs being closed due to disasters (Xiong et al., 2024); Recovery Capacity is assessed through metrics like the restoration time of major post-disaster core bus routes and the emergency reopening cycle of

primarily damaged roads (Huang Jing et al., 2020); Adaptability is reflected through indicators such as the proportion of infrastructure investment allocated to resilience enhancement projects and the level of post-disaster financial support, demonstrating the system's long-term evolutionary capacity (Kong Feng et al., 2024).

4. Application Logic and Value of DEA Efficiency Evaluation

4.1. Identification of Efficiency Patterns

The DEA-BCC model calculates the comprehensive resilience efficiency, pure technical efficiency, and scale efficiency values for cities in the Central Plains Urban Agglomeration, enabling systematic identification of regional resilience efficiency levels and spatial patterns. From a comprehensive efficiency perspective, the model distinguishes high-efficiency "resilience benchmark" cities from low-efficiency "key improvement" cities, providing a basis for sharing resilience-building experiences and pairing assistance within the region. The efficiency decomposition results indicate that cities with low pure technical efficiency demonstrate room for optimization in resource allocation, management processes, or technology application. Insufficient scale efficiency suggests a mismatch between investment scale and output level in resilience construction, requiring scale optimization through adjusted input intensity (Wu Lina, 2019). This multi-dimensional efficiency analysis enables cities to accurately identify key directions for resilience enhancement.

4.2. Projection Optimization Analysis

For inefficient cities identified by DEA, projection analysis enables quantification of input redundancy ratios and output underutilization rates, thereby defining concrete improvement targets for resilience enhancement. Based on the BCC model's projection formula, the projection point (X'_{io} , Y'_{ro}) of an ineffective decision-making unit (DMU_o) can be expressed as:

$$X'_{io} = \theta x_{io} - s_i^- \quad (i = 1, 2, \dots, m) \quad (2)$$

$$Y'_{ro} = y_{ro} + s_r^+ \quad (r = 1, 2, \dots, s) \quad (3)$$

Here, X'_{io} & Y'_{ro} represent the optimized input and output indicator values respectively. For instance, a city with high redundancy rates in soft inputs for urban management indicates resource wastage in emergency management informatization or disaster prevention publicity, requiring reduction of redundant inputs based on projection results. When critical transportation hubs show significant output deficiency during disaster-induced closures, it reveals weaknesses in their resilience. Such cases require technical upgrades or facility improvements to shorten shutdown durations to projected optimization values (Jinxi et al., 2024). The quantitative improvement pathways provided by projection analysis effectively prevent blind investments in resilience development, thereby enhancing the efficiency of public resource utilization.

4.3. Regional Coordination Reference

The DEA efficiency evaluation results can also provide references for regional coordination in building resilience within the Central Plains Urban Agglomeration. By comparing efficiency disparities between core and peripheral cities, the study identifies imbalances in resilience development under the "core-periphery" structure. Spatial

correlation analysis further reveals spatial clustering patterns of resilience efficiency, offering a basis for cross-regional resource integration, joint facility development, and emergency coordination (Lan Xue et al., 2025). For instance, in "low-low" clustered resilience-deficient areas, regional collaboration in flood control infrastructure and emergency resource sharing can be promoted, with coordinated governance efforts enhancing overall resilience levels.

5. Conclusion and Outlook

This study establishes an evaluation framework for assessing the disaster-resilience efficiency of transportation infrastructure in the Central Plains Urban Agglomeration under flood and urban flooding scenarios, utilizing the DEA-BCC model. It clarifies the theoretical foundations, indicator system, and model application logic, while incorporating standardized BCC model formulas and projection optimization formulas to enhance methodological rigor. The research demonstrates that the DEA-BCC model effectively mitigates biases in subjective weight assignment, objectively identifies efficiency disparities and improvement directions in urban resilience development, and provides precise decision-making support for regional resilience enhancement. Through scientifically designed input-output indicators, the model comprehensively reflects core dimensions of transportation infrastructure's disaster-resilience. Its efficiency decomposition and projection analysis capabilities further offer quantifiable optimization pathways for underperforming cities, thereby preventing resource wastage.

At the practical level, the DEA evaluation framework developed in this study facilitates the transition of transportation infrastructure resilience construction in the Central Plains Urban Agglomeration from "experience-driven" to "data-driven" approaches, providing a scientific basis for formulating region-specific resilience enhancement strategies. Future research could further integrate panel data and employ the Malmquist index to analyze the dynamic evolution of resilience efficiency. Additionally, combining DEA efficiency values with Tobit regression models could help identify key factors influencing efficiency disparities, thereby laying the groundwork for developing more targeted resilience optimization strategies. As research progresses, it is anticipated that this framework will offer comprehensive theoretical support and practical guidance for transportation infrastructure resilience development in the Central Plains Urban Agglomeration and similar regions nationwide.

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