2025 European Conference on Computing in Construction

CIB W78 Conference on IT in Construction

Porto, Portugal
July 14-17, 2025

POPULATION MOBILITY NETWORK CHARACTERISTICS AND ITS INFLUENCING FACTORS UNDER THE INFLUENCE OF TYPHOON BEBINCA — A CASE STUDY OF THE YANGTZE RIVER DELTA REGION

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Abstract

With the increasing frequency of extreme weather events such as typhoons, the stability and resilience of the inter-city population mobility network is facing serious challenges. Using complex-network metrics, the Pressure–State–Response framework (PSR), and a Quadratic Assignment Procedure regression (QAP), we analyze Baidu-migration data to assess Typhoon Bebinca's impact on the Yangtze River Delta population-mobility network. During landfall the network shrank, density rose, and a small-world pattern emerged; inflows to Shanghai and other cores fell sharply. One week later, connectivity rebounded. Wind magnitude, air quality, economic disparity, and pollution control significantly shaped these perturbations, whereas technology and medical capacity aided recovery. The results underline the need for multi-hub evacuation corridors and real-time data-sharing platforms to strengthen regional emergency networks.

Introduction

Typhoons, as one of the most destructive meteorological phenomena, pose significant challenges to human activities and societal systems (Qi 2014). Since the beginning of the 21st century, an average of 20 to 30 typhoons occur globally each year, causing extensive fatalities and economic losses (EM-DAT 2024). In China, typhoons result in major economic damage and loss of life annually. For example, Typhoon Bebinca, which made landfall in Shanghai in September 2024, led to direct economic losses of 1.43 billion yuan. Such disasters have spurred global and national efforts to improve disaster resilience and mitigation, with the United Nations introducing the Sustainable Development Goals in 2015 and China enhancing disaster defenses, such as the 2019 revision of the *Regulations on Meteorological Disaster Defense* (China government website 2010). Population mobility, as a key socio-economic driver, plays an essential role in disaster scenarios by influencing regional resilience and connectivity through complex mobility networks (Kraemer et al. 2020). Factors such as socio-economic development, urbanization, and transportation infrastructure have facilitated migration, making population movement a crucial component of emergency response and disaster mitigation systems (Wang *et al.* 2020). Analyzing shifts in population mobility provides insights into regional resource allocation during disasters, enabling better disaster prevention and response strategies (Pan and Lai 2019). The Yangtze River Delta (YRD), central to China's economy with its dense population and extensive transportation network, is particularly vulnerable to typhoons, which threaten both its economic stability and social systems (Yang *et al.* 2024). The region's vulnerability to frequent typhoons during the summer and fall highlights the need to understand population mobility network (PMN) to inform disaster mitigation strategies. By examining these networks, this study aims to enhance the region's resilience and emergency response capabilities.

Literature Review

Population mobility in disaster situations

Analyzing the characteristics of population movement in disaster scenarios is a highly complex research endeavor due to the diversity of disaster types, geographical variations, and differences in analytical methodologies. Moreover, the geographic and socioeconomic attributes of different regions significantly influence the structure and dynamics of PMN. For instance, Alidadi and Sharifi (2022) highlights the impact of varying built environments and anthropogenic factors on population network characteristics. Similarly, Cao et al. (2023) emphasize that the frequency, intensity, and direction of population movement are shaped by factors such as disaster severity, the timeliness of early warning systems, and the socioeconomic status of affected populations. These findings underscore the multifaceted nature of PMN and the interplay of environmental and social factors in disaster contexts.

Therefore, this study adopts complex network analysis in conjunction with the QAP and incorporates dynamic network analysis. This integrated approach allows for a comprehensive examination of the factors influencing PMN during typhoon disasters. By considering the temporal dynamics of these networks, the study aims to assess both the structural characteristics and the key determinants of population mobility in the YRD region across different phases of typhoon events.

Pressure-State-Response (PSR) model

Research on the factors influencing PMN in the context of typhoon disasters exhibits considerable diversity in perspectives, levels of analysis, and national contexts. Additionally, variations in modeling frameworks, methodologies, and theoretical underpinnings have led to significant heterogeneity in the findings of existing studies. These differences present challenges for developing a cohesive understanding of the characteristics and driving mechanisms of PMN under the influence of typhoon disasters. However, they also highlight opportunities for further exploration and refinement in this area of research. To enhance the scientific rigor and practical relevance of this study, we draw on the urban resilience assessment methodology developed by Jiao et al. (2023), which is grounded in the PSR framework. This approach provides a systematic lens for analyzing PMN and their influencing factors, contributing to a more nuanced understanding of their dynamics in disaster scenarios.

Complex network model

Complex network modeling serves as a crucial tool for understanding complex systems, offering robust theoretical support for uncovering the interaction mechanisms among multiple elements. Furthermore, the application of complex network models in urban network analysis has advanced significantly. These models are commonly employed to assess the resilience of transportation networks within urban systems (Serdar *et al.* 2022) and to analyze the structural characteristics of carbon emission networks (Huo *et al.* 2022). Specifically, complex network modeling conceptualizes PMN as complex systems comprising numerous nodes (representing regions or cities) and edges (representing population flows). By analyzing structural characteristics such as node degree, clustering coefficient, modularity, path length, and network density, these models reveal the intricate dynamics and complexity of PMN (Cai *et al.* 2024). However, existing research on the structural characteristics of urban-related networks under disaster scenarios often adopts a narrow focus. Studies tend to concentrate on a single aspect, such as analyzing the network structure before the disaster, during the disaster, or after the disaster.

Research Methodology

Study area

The urban clusters in the YRD are interconnected through a highly developed transportation infrastructure, fostering close integration among the cities. In addition, the *Outline of the Plan for the Integrated Development of the Yangtze River Delta Region*, issued by the Chinese government in 2019, emphasizes the importance of strengthening integrated ecological and green development in the region. Furthering this initiative, the *Action Program for Meteorological Protection for the Integrated Development of the Yangtze River Delta*, released in 2021, outlines comprehensive, high-quality meteorological protection measures to support the integrated development of the region. In summary, the Yangtze River Delta urban agglomeration holds significant research value due to its economic importance, high population density, and policy emphasis on sustainable development. Accordingly, this study selects the YRD urban agglomeration as its study area, as illustrated in Figure 1.

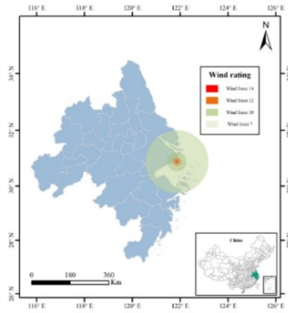

Figure 1: Study area

Variable selection

This study develops a theoretical framework for assessing the characteristics of the PMN in the YRD region under the influence of typhoon disasters. This framework is designed to identify the factors that affect the dynamics of the PMN in the YRD region. Drawing on the variable selection methodologies employed by Zhang et al. (2023), Chen et al. (2022), and Duan et al. (2020), this paper incorporates relevant variables for pressure, state, and response indicators within the PSR framework. The specific variables used to measure each indicator, along with the corresponding data and metrics, are detailed below.

Stress Indicators. Regional Wind Magnitude: This study adopts the approach of Elliott et al. (2015) using the intensity of the typhoon at the time of occurrence to measure the degree of its impact on the region. This variable is denoted as Typ. Response Indicators: Education Level: Referring to the work of Lupu and Nuţă (2023), the regional education level is measured by education expenditure, denoted as Edu; Science and Technology Level: Following the methodology of Su and Fan (2022), the regional science and technology level is assessed using research and development (R&D) expenditure, denoted as Sci; Economic Development Level: This paper draws on the study by Li and Wu (2023), measuring the level of economic development by total regional GDP, denoted as Eco; Medical Care Level: Based on Winkelmann et al. (2022), the regional medical care level is measured by the number of practicing physicians, denoted as Med; Pollution Control Level: Adopting the approach of Chen et al. (2021), the regional level of pollution control is measured by the utilization rate of general industrial solid waste, also denoted as Pol. Status Indicators: Air Quality Level: Referring to the work of Zhang et al. (2024), this study measures air quality using the good air quality rate, expressed as Air; Forest Cover Level: Regional forest coverage is assessed using the forest cover rate, denoted as For; Agricultural Development Level: Following Zhang et al. (2022), the level of agricultural development is measured by the cultivated land area, expressed as Agr; Residents' Economic Conditions: Referring to the methodology of Wang et al. (2015), the economic conditions of regional residents are measured using GDP per capita, denoted as Res.

Network characterization

First, this study integrates the population migration data collected for the YRD region between September 10, 2024, and September 29, 2024. Using this data, the originating and destination cities of migration are defined as the nodes in the PMN, while the volume of population movement between these nodes represents the connecting edges. This process ultimately constructs the PMN for the YRD region and establishes its corresponding relational matrix. Secondly, this paper analyzes the average path length, average clustering coefficient, degree of modularity, network density, and giant component size (GCS) of the PMN in the YRD region by means of complex network analysis.

QAP Analysis

QAP analysis is a social network analysis method grounded in graph theory and matrix theory, making it particularly well-suited for examining correlations between matrices and analyzing influencing factors. Unlike traditional multiple regression analysis, QAP analysis does not require the assumption of independence, enabling the inclusion of all relevant influencing variables within the model. Drawing on the work of Dong and Li, this study employs the QAP analysis method to construct a regression model. In this model, the PMN matrix of the YRD region serves as the dependent variable, while the difference matrices of the influencing factors—identified through the evaluation index system of the YRD PMN under the influence of typhoons—are used as independent variables. Characterization of PMN.

Characterization of population mobility network

Changes in the size of PMN

As shown in Figure 2, this study analyzes the impact of typhoons on the PMN in the YRD region across three stages: before, during, and after the typhoon. Mobility routes with volumes exceeding 3,000 were visualized to assess changes in network structure. The YRD mobility network is spatially characterized by being "dense in the east and sparse in the west," with flows concentrated around Shanghai, Hangzhou, Nanjing, and Suzhou, and notable connections to Beijing, Shenzhen, and the Central Plains. The core cities exhibit the highest density, with connectivity decreasing toward the periphery. Before the typhoon, the network was expansive but less dense, with significant long-distance flows, especially to Beijing and Shenzhen. During the typhoon, the network contracted, density increased, and mobility shifted to short-distance movements among coastal cities and provincial capitals, as long-distance travel halted due to infrastructure disruptions. After the typhoon, the network rapidly recovered, expanding in size and resuming long-distance flows.This demonstrates the YRD region’s strong resilience and adaptive capacity, as the mobility network quickly returned to its pre-typhoon state.

Degree centrality analysis

As shown in Figure 3, this study analyzes the degree centrality of cities in the YRD region before, during, and after the typhoon, revealing dynamic trends in population inflows. Before the typhoon, the degree centrality of the PMN was relatively balanced, with cities like Shanghai, Suzhou, and Hangzhou serving as key hubs for population flows. Inflows to most cities remained stable. During the typhoon, population inflows across the region dropped significantly, with Shanghai experiencing the largest decline. This decrease led to a redistribution effect, boosting inflows to neighboring cities such as Nanjing, Zhenjiang, Nantong, and Yancheng, indicating a radial shift in mobility patterns. As the typhoon’s impact subsided, population inflows rebounded sharply, often exceeding pre-typhoon levels. Cities like Shanghai, Suzhou, Hangzhou, Ningbo, and Jinhua demonstrated strong reattraction capacity. Post-typhoon, inflows returned to normal levels, exhibiting stable cyclical patterns. These findings highlight the YRD region's robust resilience and adaptability, as its PMN quickly recovered from short-term disruptions caused by the typhoon.

Changes in network structural characteristics

This study uses complex network analysis to explore the structural characteristics of the PMN in the YRD region during typhoons. The GCS indicator shows a significant decrease in network connectivity during the typhoon, highlighting weakened inter-city linkages. In contrast, the Network Density indicator rises, suggesting shorter-distance movements due to disruptions in long-distance transportation. The Modularity indicator increases, reflecting the formation of tight-knit groups as populations migrate to evacuation hubs, and the emergency response network strengthens regional collaboration. The Average Path Length remains stable, indicating minimal fragmentation of the network, while the Average Clustering Coefficient rises, showing enhanced local connectivity and cohesive substructures among cities. These changes emphasize the PMN’s adaptability and resilience during typhoons. In summary, this study analyzes the dynamics of the PMN in the YRD region using a complex network model. The findings reveal that during the typhoon period, the network exhibited a reduction in scale and an increase in density, with population movements shifting predominantly toward short-distance mobility. Once the typhoon's impact subsided, the PMN demonstrated a strong capacity for recovery, quickly returning to its pre-typhoon state. Additionally, the modularity of the network increased significantly during the typhoon, indicating the expansion of emergency response modules and underscoring the critical role of the region's emergency management system in mitigating the disaster’s effects.

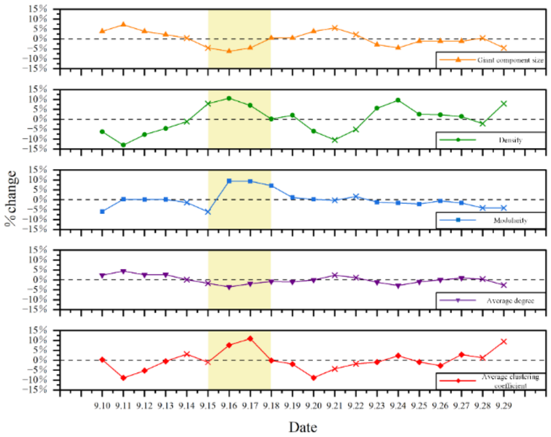

Figure 3: Results of complex network analysis
Note: Note: Solid dots are for weekdays; “x” dots are for weekends.

Small-World Properties of the PMN

The simultaneous rise in the average clustering coefficient (+19 %) and the persistence of a short mean path length (2.8 – 3.2 hops) during landfall reveal that the Yangtze River Delta mobility graph exhibits a pronounced small-world topology. Such a configuration combines dense local cohesion with efficient global reach: populations can relocate rapidly through a few high-betweenness “long-range” links even while most travel concentrates within tightly knit city clusters. This duality explains why the network maintained overall connectivity after Shanghai lost 27 % of its edges and why post-event recovery was swift. Operationally, protecting a minimal set of inter-cluster bridges (identified via betweenness centrality) would preserve system accessibility under stress and should therefore become a priority in regional evacuation and infrastructure-hardening plans.

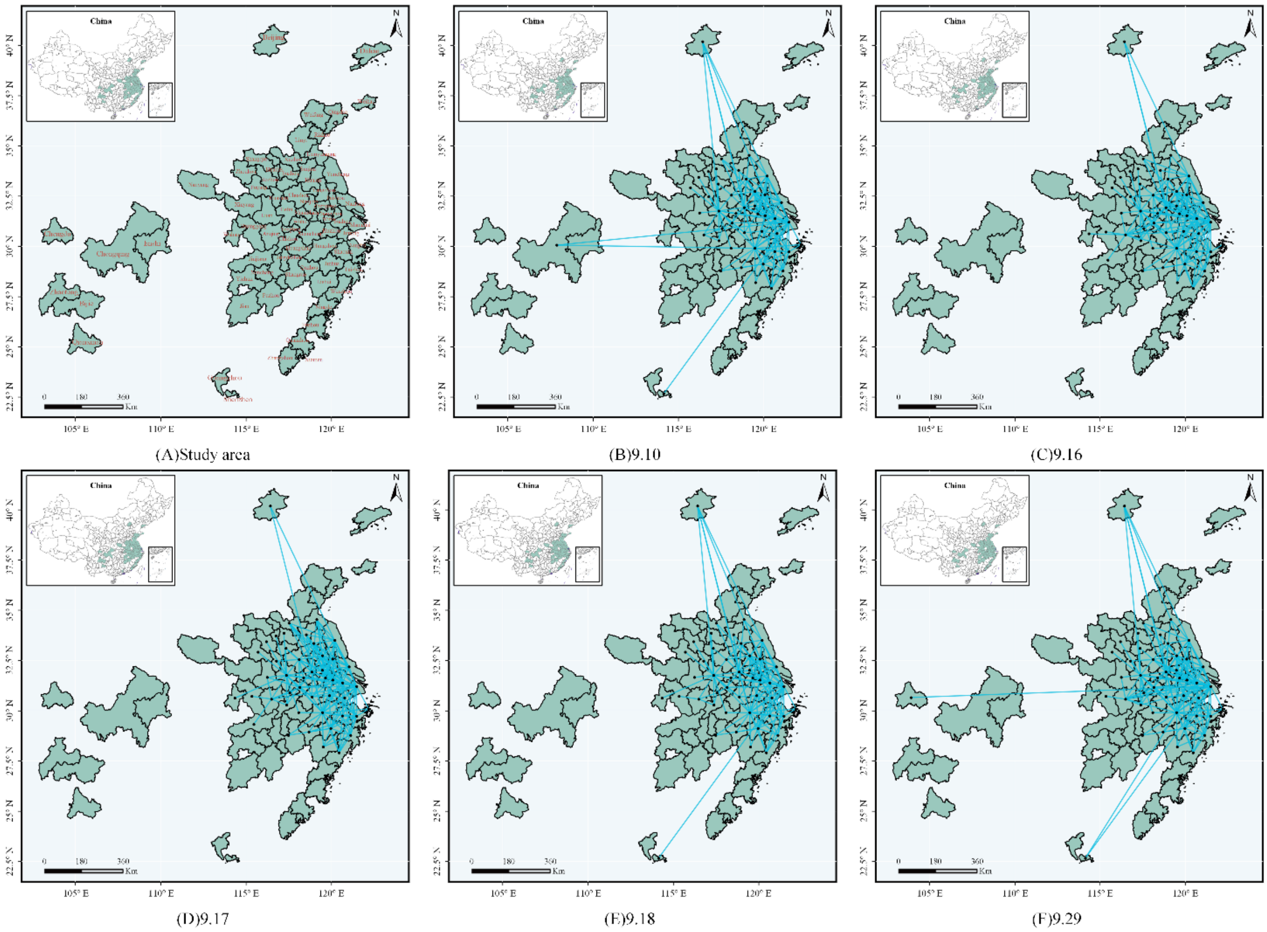

Figure 2: Changes in the structure of population mobility networks

Analysis of influencing factors

QAP correlation analysis

As shown in Table 1, wind magnitude, agricultural development level, air quality, pollution control, economic conditions of residents, and forest cover exhibit significant negative correlations with the YRD PMN. These correlations are most pronounced during the typhoon's landfall but gradually return to pre-typhoon levels over time. Conversely, economic development level, education level, technology level, and medical care level show significant positive correlations with the PMN.

These positive correlations also fluctuate during the typhoon but eventually stabilize, aligning with pre-typhoon levels.

Table 1. QAP correlation analysis results

Variables	Sep 10th		Sep 16th		Sep 17th		Sep 24th	
	Pearson correlation	P-Value	Pearson correlation	P-Value	Pearson correlation	P-Value	Pearson correlation	P-Value
Typ	-0.073**	0.022	-0.094***	0.004	-0.106***	0.001	-0.086***	0.002
Eco	0.090*	0.056	0.069*	0.094	0.094**	0.049	0.077*	0.062
Agr	-0.113***	0.000	-0.098***	0.001	-0.095***	0.000	-0.103***	0.000
Edu	0.080*	0.081	0.067*	0.098	0.091*	0.065	0.082*	0.075
Air	-0.156***	0.000	-0.173***	0.000	-0.150***	0.000	-0.129***	0.000
R&D	0.101**	0.043	0.115**	0.024	0.132**	0.011	0.087**	0.067
Res	-0.079***	0.008	-0.079**	0.012	-0.070**	0.016	-0.084***	0.004
For	-0.060**	0.032	-0.059**	0.039	-0.045*	0.092	-0.046*	0.079
Med	0.061*	0.091	0.051*	0.097	0.057*	0.093	0.060*	0.092
Pol	-0.081**	0.026	-0.075**	0.047	-0.077**	0.044	-0.080**	0.031

QAP regression analysis

In this paper, September 10, September 16, September 17 and September 24 are selected to represent the population flow network of the Yangtze River Delta region before the typhoon landfall, at the time of the typhoon landfall, and after the typhoon landfall, and are transformed into the form of adjacency matrices as the dependent variable network matrices. At the same time, the difference matrix of the variables that passed the QAP correlation test was used as the dependent variable in the regression model, and the number of random permutations was set to be 2,000, and the specific regression results are shown in Table 2.

Wind magnitude consistently has a negative impact on the PMN in the YRD region, intensifying with typhoon severity as transportation modes like air and rail are restricted, reducing mobility. However, the network recovers to pre-typhoon levels once the typhoon subsides. Air quality differences also negatively affect mobility, as higher pollution deters migration to affected areas, particularly those with severe pollution. Economic disparities influence mobility, with wealthier areas demonstrating greater stability and disaster management capacity, mitigating disruptions during typhoons. Differences in pollution governance similarly affect the PMN, as regions with stronger pollution control experience less severe impacts, emphasizing the need for enhanced pollution management and emergency responses in high-pollution areas to ensure recovery and stability. During non-typhoon periods, economic and agricultural development disparities significantly impact mobility, with higher economic development driving migration through better opportunities, infrastructure, and living standards, while agriculturally dominated areas attract fewer migrants. These effects diminish during typhoons, as the focus shifts to risk aversion and emergency resources. Differences in education levels and forest cover do not significantly impact the PMN, likely due to the widespread dissemination of education, slow changes in forest cover, and effective environmental protection policies. These findings highlight the dynamic nature of mobility determinants before, during, and after disasters.

Table 2. QAP regression analysis results

Varables	Sep 10th		Sep 16th		Sep 17th		Sep 24th	
	Stdized Coef	P-Value	Stdized Coef	P-Value	Stdized Coef	P-Value	Stdized Coef	P-Value
Typ	-0.069**	0.030	-0.096***	0.003	-0.074**	0.023	-0.042**	0.080
Eco	0.287**	0.031	0.118	0.234	0.077	0.285	0.243**	0.050
Agr	-0.075*	0.069	-0.056	0.158	-0.050	0.165	-0.075*	0.069
Edu	-0.103	0.273	0.064	0.388	0.230	0.119	-0.018	0.432
Air	-0.120***	0.000	-0.146***	0.000	-0.129***	0.000	-0.102***	0.000
R&D	0.065	0.189	0.171**	0.049	0.160*	0.054	0.052	0.223
Res	-0.166***	0.000	-0.109***	0.008	-0.120***	0.001	-0.144***	0.001
For	-0.004	0.484	0.025	0.338	0.042	0.226	-0.011	0.414
Med	-0.075	0.192	-0.211*	0.072	-0.333**	0.021	-0.064	0.249
Pol	-0.073**	0.042	-0.074**	0.047	-0.075**	0.049	-0.069**	0.029
R^2	0.165		0.170		0.169		0.151	
Perms	2000		2000		2000		2000	

Policy implications

Collectively, these statistical relationships provide a practical lens through which regional authorities can translate empirical evidence into targeted disaster-management actions. Network shrinkage and modular re-clustering during landfall indicate that regional emergency planners should: (i) pre-position shelters and medical resources at secondary hubs such as Suzhou and Ningbo, creating multi-hub evacuation corridors rather than relying solely on Shanghai; (ii) deploy a real-time, joint mobility-data command platform so that road clearance and rail re-opening can be prioritized according to network backbone indicators (giant-component size, betweenness); and (iii) incorporate those indicators into provincial contingency plans to raise overall system resilience. Implementing these measures can shorten disruption time and accelerate post-event recovery for the Yangtze River Delta and other typhoon-exposed megaregions.

Conclusions

This study develops a framework to analyze the PMN in the YRD region during typhoons, using the PSR model and complex network analysis with Baidu migration data (Sept 10-29, 2024). It finds that the typhoon reduced network size, increased density, and shifted mobility to neighboring cities, forming a "small world" phenomenon. Post-typhoon, mobility and network size recovered. Degree centrality analysis shows a drop in Shanghai's inflows during the typhoon, which rebounded afterward. Factors like wind magnitude, air quality, economic conditions, and pollution control negatively impacted mobility, while science, technology, and medical care played significant roles during the typhoon. Two data-related limitations warrant caution: Baidu Migration records only mobile-phone users and provides daily aggregates, potentially missing sub-daily or informal travel, and PSR covariates rely on annual statistics that are temporally misaligned with the mobility series. Future work should fuse higher-frequency, multi-source mobility feeds with quarterly socio-economic indicators and compare multiple extreme-weather events to strengthen causal inference and generalizability.

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