Identification and Analysis of Peak Population Migration Patterns in the Beijing-Tianjin-Hebei Region Based on Complex Network Theory

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Abstract

As a vital economic and population agglomeration area in China, the Beijing-Tianjin-Hebei region has attracted considerable attention regarding population migration issues. Population migration not only directly affects the population size and structure of cities within the region but also has profound implications for economic development, social stability, and urban planning. This study extends the analysis to the "Spring Festival Travel Rush" period, using population migration data from January to March in the years 2020 to 2022 as the basis. By employing complex network theory and relevant statistical indicators, the study explores the peak period population migration patterns and their variations in the Beijing-Tianjin-Hebei region. The research firstly identifies significant changes in population migration patterns in the Beijing-Tianjin-Hebei region around 2021 and analyzes the changing patterns. Secondly, network statistical indicators indicate hierarchical population migration patterns based on city tiers. Furthermore, cities with unique migration patterns are identified. Finally, based on an in-depth exploration of population migration patterns and their variations in the Beijing-Tianjin-Hebei region, the study provides suggestions and prospects for future urban planning and development, offering important references for addressing the challenges posed by population migration in the region.

1. Introduction

In the era of globalization, population mobility between cities and regions significantly impacts urban development and regional economies(Chen et al., 2018). The Beijing-Tianjin-Hebei region, a key economic and demographic center in China, attracts attention for its migration trends. With rapid economic development and accelerated urbanization, profound changes are also occurring in the patterns and trends of population migration in the Beijing-Tianjin-Hebei region. Population movement affects urban development, resource allocation, and social stability(He and Shao, 2018). Thus, analyzing migration in this region is crucial for regional coordination, urban planning, and demographic optimization. China's migration research dates to the 1970s, initially focusing on post-war regions like the Soviet Union. It's now a multidisciplinary field covering social sciences, demography, and regional studies. Scholars study migration drivers, patterns, effects, and policies using various methods and theories. Early studies used statistics and census data, showing city clusters' significant influence on migration and urbanization(Gu and Cai, 1999). Early population migration studies primarily relied on statistical data and census data as the main sources of information. These studies identified significant impacts of city clusters such as the "Beijing-Tianjin-Hebei", "Pearl River Delta", and "Yangtze River Delta" on population migration and urbanization.

Internet companies utilize location data from hundreds of millions of users to obtain daily population movements between spatial units at various levels. Such big data possesses reasonably accurate time and location information, with high precision(Wang and Shi, 2021). Currently, it has been applied in various directions related to population migration and urbanization, including the spatial patterns of urbanization under population migration, population migration tendencies in urban agglomerations, and the relationship between population migration and housing price changes. Traditional studies often focused on migration flows in a single direction, with limited capacity to study comprehensive migration models between multiple units within a region. The emergence of new technologies has brought about a shift in research methods, with the introduction of complex network theory providing new tools and perspectives for uncovering the complexity of the internal structure of population migration systems and the multidimensionality of migration flows. By viewing population migration as a network composed of multiple nodes and edges, it is possible to delve deeper into the structural characteristics and evolutionary patterns of population movement, providing new perspectives and methods for addressing practical problems(Pan and Lai, 2019).

Ordinary population migration often exhibits characteristics of one-time and irregular patterns, lacking a specific time schedule. The "Spring Festival Travel Rush," as a unique social phenomenon, differs significantly from ordinary population migration. It is formed within the specific cultural context of China, characterized by regular and collective spatial-temporal behaviors(Feng et al., 2019). The "Spring Festival Travel Rush" encompasses the entire process of people returning to their hometowns before the Spring Festival and then returning to their places of residence after the festival. During the Spring Festival Travel Rush, hundreds of millions of people flock to transportation hubs, creating a massive influx of population movement, which to a certain extent reflects the unique operational rules of Chinese society and economy. By exploring such phenomena and employing complex network theory, this study aims to understand migration patterns over time, informing urban planning.

This study extends the analysis to the "Spring Festival Travel Rush" period, focusing on population migration from January to March in the years 2020 to 2022. By applying complex network theory, the study aims to reveal the migration patterns and their variations during peak migration periods across different years. Complex network theory enables a deep analysis of the complexity of population migration from the perspectives of

network structure and relationships between nodes. It facilitates a better understanding of the patterns and influencing factors of population migration, unveiling the dynamic characteristics and regularities of population migration during different time periods. This study provides scientific references for future urban planning and development.

2. Research area and data sources

2.1 Research area

The research area in northern China covers major cities and provinces in the Beijing-Tianjin-Hebei region, including Beijing, Tianjin, and parts of Hebei Province (Figure 1). As an economic and population hub of China, the Beijing-Tianjin-Hebei region is renowned for its abundant resources, developed economy, and dense population. Beijing, as the political, economic, and cultural center, carries significant national responsibilities and missions. Its large population base and international urban environment attract a considerable influx of talented individuals. Tianjin, serving as an international trade hub and an important port city, attracts numerous migrants due to its convenient transportation and abundant resources. Hebei Province is characterized by its rich natural resources and significant industrial base, closely linked with Beijing and Tianjin, and serves as a major supplier of labor and resources.

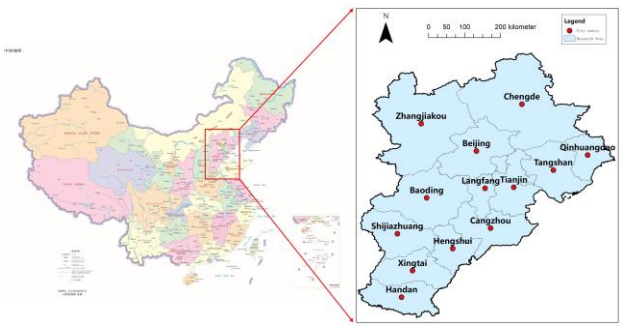


Figure 1. Research area.

According to the urban hierarchy of the Beijing-Tianjin-Hebei region classified by the United Nations' China Urban Rankings in 2021 and 2022 (Table 1), the inter-city population flow forms complex and diverse migration patterns, profoundly impacting the region's economic, social, and urban development. Therefore, understanding the dynamics of population migration in the Beijing-Tianjin-Hebei region and its implications for urban planning and development is of great significance. It helps in formulating more scientific and effective policy measures to promote the sustainable development of the Beijing-Tianjin-Hebei region.

Urban Hierarchy	City Names
First-tier cities:	Beijing
Near first-tier cities:	Tianjin
Second-tier cities:	Shijiazhuang, Baoding
Third-tier cities:	Xingtai, Handan, Cangzhou, Tangshan, Langfang
Fourth-tier cities:	Zhangjiakou, Chengde, Qinhuangdao, Hengshui

Table 1. Classification of city tiers in the Beijing-Tianjin-Hebei region

2.2 Data Sources

The population migration data used in this study is sourced from Baidu Migration Data (https://qianxi.baidu.com), a platform that aggregates and analyzes large-scale user location information based on Baidu Maps and location data. This data includes population migration flow, migration trends, and other relevant information. The dataset covers population migration in the Beijing-Tianjin-Hebei region from January to March in the years 2020 to 2022, including information on cities of departure, cities of arrival, and migration indices, which measure the scale of population migration. The research scope encompasses all prefecture-level cities in the Beijing-Tianjin-Hebei region, such as Beijing, Tianjin, Shijiazhuang, Tangshan, Qinhuangdao, Handan, Xingtai, Baoding, Zhangjiakou, Chengde, Cangzhou, Langfang, and Hengshui. Additionally, Chinese map data from the Standard Map Service Network (http://bzdt.ch.mnr.gov.cn/) was utilized. Administrative division data for the Beijing-Tianjin-Hebei region was obtained from the "River Map Annotation" website (http://www.rivermap.cn/) and can also be downloaded from the OSM website (https://www.openstreetmap.org/). The data retrieval was conducted in June 2022.

3. Methodology

Complex network theory is an important mathematical and computational tool used to study the interactions between nodes in various complex systems(Liu and Chen, 2005). Its core objective is to explore and reveal the underlying patterns and properties of network structures. Population migration between different cities forms a directed weighted network, known as a population migration network. Each city represents a node in the network, and the migration relationships between cities constitute the edges of the network. The direction of the edges represents the direction of population migration, while the weight of the edges reflects the magnitude of migration, i.e., the number of migrants. Based on the population migration network, various network statistical indicators can be used to conduct in-depth analysis of population migration patterns.

3.1 Node strength

Node strength measures a node's connectivity in a network, reflecting its importance. It equals the sum of weights of all connected edges. In directed networks, it splits into out-degree (outgoing connections) and in-degree (incoming connections). Equations:

$$S_{in}(i) = \sum_{j \in v_{in}} W_{ij} \; ; S_{out}(i) = \sum_{j \in v_{out}} W_{ij} \; , \quad (1)$$

$$NFR = \frac{S_{in}(i) - S_{out}(i)}{S_{in}(i) + S_{out}(i)} \quad (2)$$

where $S_{in}(i)$, $S_{out}(i)$= node i's in-strength and out-strength
v_{in} = set of nodes flowing into node i
v_{out} = set of nodes to which node i flows
W_{ij} = edge weight
NFR = net flow ratio

NFR is used to assess the degree of aggregation or dispersion of nodes. When the NFR value approaches 1, it indicates that the city tends to experience population aggregation; when the NFR value approaches -1, it suggests that the city tends to experience population loss; when the NFR value approaches 0, it signifies that the city is in a state of population migration balance.

3.2 Centrality

Network centrality measures node importance and influence. This study uses degree and betweenness centrality to assess node connectivity and intermediary role, reflecting city significance in population migration. Betweenness centrality quantifies a node's mediation level in complex networks, indicating its capacity for information, resource, or influence mediation. Equations:

$$C_B(i) = \sum_{s \neq i \neq t} \frac{\sigma_{st}(i)}{\sigma_{st}} \quad (3)$$

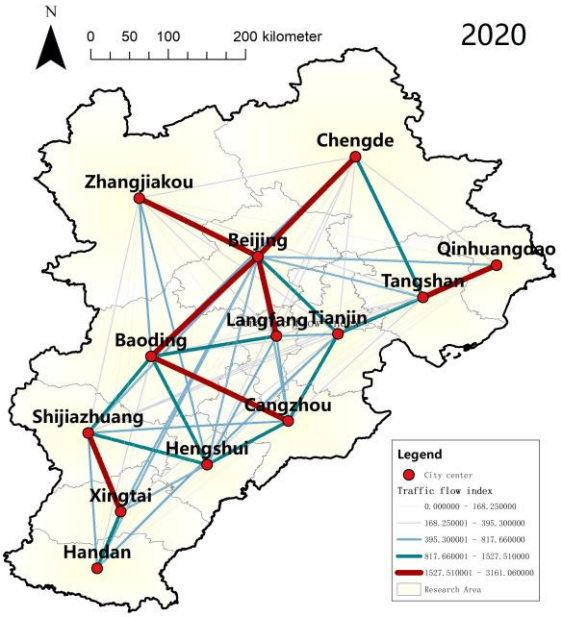
where $C_B(v)$= node i 's betweenness centrality
σ_{st} = number of shortest paths from node s to node t
$\sigma_{st}(v)$= number of shortest paths from node s to node t passing through node i

4. Experiment

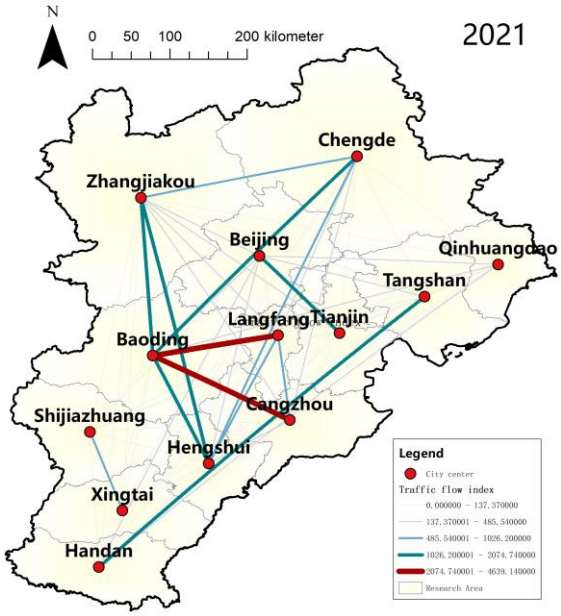
4.1 Network Construction and Analysis

The spatial visualization of the population migration network and node strength calculation results is shown in Figure 2. In this figure, the traffic index is used to measure the magnitude of population migration between cities, while the node strength measures the total population migration volume with city nodes as the origin or destination, i.e., the total migration volume. Both the traffic index and node strength are classified using natural breaks.

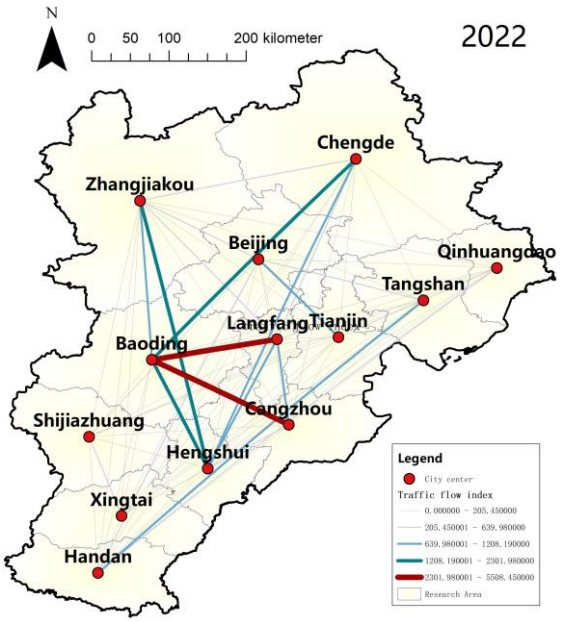
By 2021, there are noticeable changes in the network structure of population migration (Figure 2(b)). Firstly, the overall migration activity within the study area decreases significantly, with reduced migration volumes between most cities compared to 2020. Secondly, both the node strength and edge weight indicate a shift in the population migration center from Beijing to Baoding. Although there are still migration relationships between Beijing and surrounding cities, the migration volume is significantly lower than that of Baoding. The migration activities between Baoding-Langfang and Baoding-Cangzhou are the two highest in the Beijing-Tianjin-Hebei region. Therefore, Baoding becomes the central city for population migration from January to March 2021, forming a Baoding-Langfang-Cangzhou population migration triangle with Baoding as the core.



(a) 2020



(b) 2021



(c) 2022

Figure 2. Population migration network.

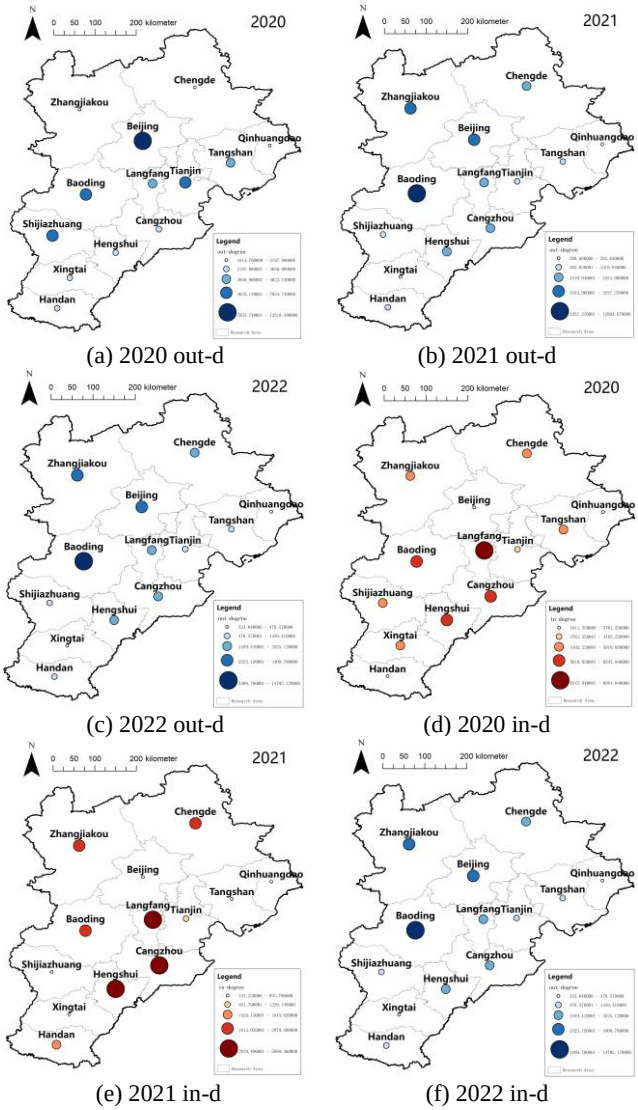
The network structure in January-March 2022 (Figure 2(c)) is similar to that in 2021. Migration activity decreases again, especially in Beijing and surrounding cities. Baoding remains the central city for migration, and the Baoding-Langfang-Cangzhou population migration triangle, with the highest migration volume in the Beijing-Tianjin-Hebei region, continues to be maintained.

The change in network structure from 2020 to January-March 2022 indicates a shift in population migration pattern in the Beijing-Tianjin-Hebei region from a diffusion pattern with Beijing as the core to a triangular pattern with Baoding as the core. The distribution of population migration volume shifts from multiple pairs of cities with relatively high and equal migration relationships to concentrated migration relationships between Baoding-Langfang and Baoding-Cangzhou.

4.2 Network Node Strength Analysis

The spatial visualization of the node in-degree and out-degree calculation results (Figure 3) is classified using natural breaks according to the degree values. Based on the calculation results of node in-degree and out-degree, in January-March 2020 (Figure 3(a), (d)), the city with the highest out-degree is Beijing, followed by Tianjin, Shijiazhuang, and Baoding. The city with the highest in-degree is Langfang, followed by Baoding, Hengshui, and Cangzhou, while the rest of the cities have relatively low in-degree and out-degree values. Beijing and Langfang are the two cities with the highest population migration tendencies that year. Beijing has the highest out-degree, indicating a larger number of outbound migrants and relatively fewer inbound migrants. Cities with similar population migration tendencies include Tianjin and Shijiazhuang. On the other hand, Langfang has the highest in-degree, indicating a larger number of inbound migrants and relatively fewer outbound migrants. Cities with similar population migration tendencies include Hengshui and Cangzhou. Only Baoding exhibits a dual population migration tendency, with both a high out-degree and a high in-degree.

The distribution of in-degree and out-degree of each city remains consistent in 2021 and January-March 2022 (Figure 3(b), (c), (e), (f)). The city with the highest out-degree is Baoding, followed by Beijing and Zhangjiakou. The cities with the highest in-degree are three: Langfang, Cangzhou, and Hengshui, followed by Baoding, Zhangjiakou, and Chengde, while the rest of the cities have relatively low in-degree and out-degree values. Baoding remains the city with the highest inbound migration volume in the Beijing-Tianjin-Hebei region while also having the highest outbound migration volume. Adjacent cities such as Langfang, Cangzhou, and Hengshui show significant inbound migration tendencies with notably high inbound migration volumes. Additionally, Beijing exhibits a weaker outbound migration tendency, and Zhangjiakou exhibits a dual population migration tendency.



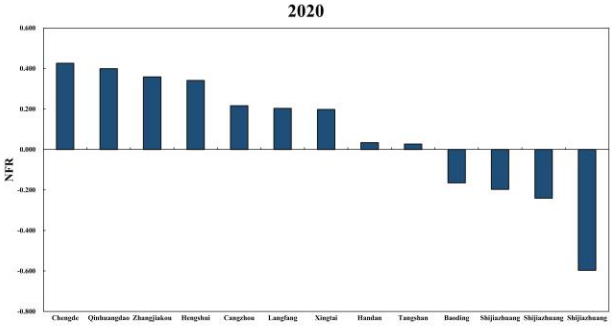
(a) 2020 out-d (b) 2021 out-d

(c) 2022 out-d (d) 2020 in-d

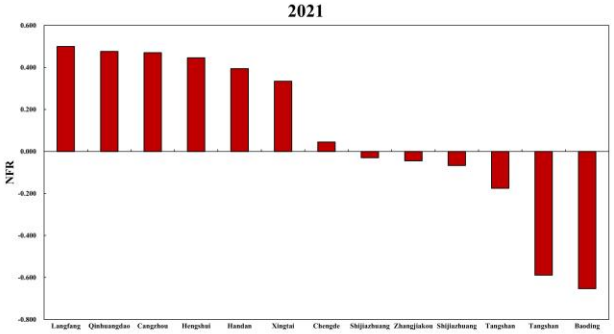
(e) 2021 in-d (f) 2022 in-d

Figure 3. Node Strength Analysis.

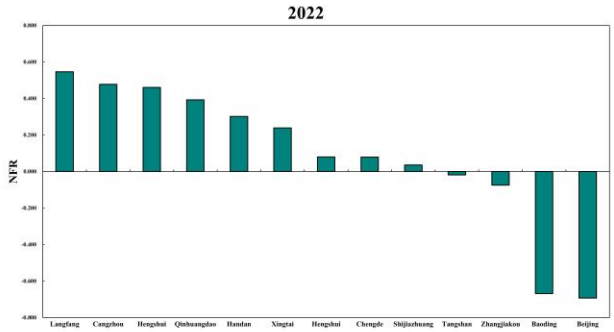
Based on the in-degree and out-degree of nodes, the NFR from January to March for the years 2020 to 2022 was calculated to evaluate the overall population change in each city. If the NFR is positive, the city's population is increasing; if negative, the population is decreasing. The results, sorted in descending order, are shown in Figure 4.



(a) 2020 NFR



(b) 2021 NFR



(c) 2022 NFR
Figure 4. NFR Analysis.

In January to March 2020 (Figure 4(a)), the number of cities with a positive NFR was higher. The city with the highest positive NFR was Chengde, followed by Qinhuangdao, Zhangjiakou, Hengshui, and others. The city with the highest negative NFR was Beijing, followed by Tianjin, Shijiazhuang, and Baoding. According to Table 1, these four cities are all second-tier or higher in the Beijing-Tianjin-Hebei region. Therefore, the overall trend in population migration for 2020 shows a decrease in population in first- and second-tier cities and an increase in third- and fourth-tier cities.

4.3 Network Centrality Analysis

In January to March 2021, Langfang had the highest NFR (Figure 4(b)), followed by Qinhuangdao, Cangzhou, and Hengshui. Baoding had the highest negative NFR, followed by Beijing. The NFR ranking for 2022 was similar to that of 2021 (Figure 4(c)), with Langfang again having the highest positive NFR, followed by Cangzhou, Hengshui, and Qinhuangdao. The city with the highest negative NFR was Beijing, followed closely by Baoding. Hence, in both 2021 and 2022, the cities with the most significant population loss were Baoding and Beijing, while other cities experienced smaller losses. The cities with increasing populations were all third- and fourth-tier cities.

According to the calculations of betweenness centrality shown in Figure 5, an analysis was conducted on the degree of intermediacy and the importance of connecting other nodes for each city in the population migration network from 2020 to March 2022. The results for 2020 indicate that Xingtai has the highest betweenness centrality, indicating its strong intermediary role in the population migration network as a crucial hub connecting other cities. Qinhuangdao ranks second, while Chengde and Langfang have slightly higher betweenness centrality values than other cities, though still relatively low. The betweenness centrality of the remaining cities is lower and equal. In 2021, Xingtai remains the city with the highest betweenness centrality, followed by Langfang and Shijiazhuang, with Hengshui and Cangzhou closely trailing behind. The results for 2022 show that Xingtai continues to have the highest betweenness centrality, followed by Langfang, Shijiazhuang, and Cangzhou.

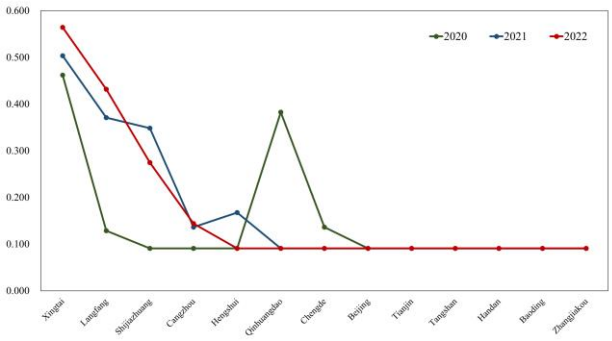


Figure 5. Centrality Analysis.

5. Conclusion

5.1 Summary of Population Migration Mechanisms

This study combines Baidu migration data from January to March of 2020 to 2023 for the Beijing-Tianjin-Hebei region. Using complex network theory, we constructed a population migration network and analyzed migration patterns based on network statistical indicators. The results indicate:

(1) Analysis of the network structure and statistical indicators for each year reveals a significant change in the migration patterns in the Beijing-Tianjin-Hebei region from January to March of 2021, which persisted in 2022. The main changes can be summarized in two points: first, the overall migration activity shifted from widespread migration among many cities to concentrated migration among fewer cities. Second, the migration center of the Beijing-Tianjin-Hebei region shifted from Beijing to Baoding, changing from a diffusion pattern centered on Beijing to a triangular migration pattern centered on Baoding, Langfang, and Cangzhou. These changes in migration patterns were influenced by multiple factors, with the COVID-19 pandemic starting in 2020 being a major one. Beijing's special status resulted in stricter policies and control measures, limiting population movement and reducing migration in and out of the city. As a result, overall migration activity in the Beijing-Tianjin-Hebei region declined. Baoding, being close to Beijing and having a relatively developed economy, became a popular migration destination due to its lower pandemic risk and more flexible policies.

(2) The Beijing-Tianjin-Hebei region exhibits different migration patterns based on city tiers. From 2020 to 2022, migration patterns showed that first- and second-tier cities

primarily experienced population outflows, while third- and fourth-tier cities primarily experienced population inflows. There are two main reasons for this tiered migration pattern. First, the population in first- and second-tier cities has reached near their capacity, leading to problems such as congestion and increased living costs, which drive population outflows. Second, with the implementation of the Beijing-Tianjin-Hebei region's coordinated development strategy, the rapid development of third- and fourth-tier cities has become a significant trend. The steady rise in the living index and various preferential policies, such as talent introduction by the government, have further promoted population inflows.

(3) Analysis of the migration characteristics of individual cities identified several cities with unique migration patterns. Cities with dual migration tendencies include Baoding in 2020 and Zhangjiakou from 2021 to 2022, both having high migration inflows and outflows. Xingtai consistently showed the highest betweenness centrality over the three years, significantly higher than other cities. Baoding and Zhangjiakou, with their well-developed industrial structures and infrastructure, along with various governmental talent and investment policies, attracted a large influx of migrants. Simultaneously, residents might choose to move to other cities or return to their hometowns for reasons such as job opportunities, educational resources, or living environment. Xingtai, as a key transportation node in the Beijing-Tianjin-Hebei region, plays a crucial role as a transit point and in forming connections with other cities, highlighting its strong transportation links with other cities.

5.2 Recommendations and Outlook

After examining the changes and characteristics of population migration patterns in the Beijing-Tianjin-Hebei region, this study proposes the following specific recommendations to address current challenges and promote future development:

(1) Population Redistribution in Mega Cities. With the shift in population migration patterns in the Beijing-Tianjin-Hebei region, the government should adopt more targeted policy directions. Primarily, it is crucial to alleviate the population pressure in mega cities by optimizing migration policies and encouraging the relocation of people to economically underdeveloped areas and emerging cities. This would facilitate the rational distribution of resources and population. Mega cities like Beijing face significant challenges due to overpopulation. The government can mitigate this by encouraging enterprises to move to second-tier cities, providing policy support to achieve population decentralization and resource optimization.

(2) Strengthening Urban Infrastructure. For cities experiencing high population inflows, such as Langfang, Cangzhou, and Hengshui, the focus should be on transportation, education, and healthcare. Increasing investment in these areas can enhance the attractiveness and competitiveness of these cities, improving residents' quality of life. For cities with significant population outflows, such as Baoding, it is essential to analyze the reasons behind this trend, whether it is due to reduced employment opportunities, rising housing prices, or environmental issues. Efforts should be made to improve the employment environment, attract business investment, and offer more job opportunities. The government should formulate relevant policies and provide funding and resources to support urban development and improvement. Additionally, enhancing cooperation with neighboring cities to address regional issues collectively can promote development in the Beijing-Tianjin-Hebei region. For cities with high betweenness centrality, like Xingtai, which play a pivotal role in regional connectivity, special attention should be given to the construction of transportation and related infrastructure.

The findings of this study provide important references for future urban planning and development, helping to better understand the impact of population migration on urban growth and to take appropriate measures to address challenges, fostering sustainable regional development and social stability. Future changes in population migration patterns in the Beijing-Tianjin-Hebei region will be influenced by various factors such as economic development, policy adjustments, and pandemic control. In future planning, cities should actively respond to these challenges, strengthen cooperation, and jointly promote the socio-economic development of the Beijing-Tianjin-Hebei region, achieving a positive cycle and sustainable development in population migration.

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