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The Structural and Functional Development of an Urban Network System from the Perspective of Flow Space: A Case Study of Nanjing

Lizhen Shen [1,*], Xiaorui Lv [1], Shuyu Zhang [2], Peipei Chen [1], Pu Cheng [3] and Shenyu Liu [4]

[1] School of Architecture and Planning, Nanjing University, Nanjing 210093, China; 522023360105@smail.nju.edu.cn (X.L.); p.chen@nju.edu.cn (P.C.)
[2] Nanjing Municipal Bureau of Planning and Natural Resources, Jiangning Branch Bureau, Nanjing 211100, China; zsy666529@outlook.com
[3] Jiangsu Provincial Planning and Design Group, Jiangsu Institute of Urban Planning and Design, Nanjing 210000, China; chengpu@jspdg.com
[4] School of Foreign Languages, Peking University, Beijing 100080, China
* Correspondence: shenlizhen@nju.edu.cn

Abstract: Globalization and informatization have exerted far-reaching impacts on the spatial connection and development of urban systems. This study, concerning the network of an urban system based on the space of flows, supplements the insufficiency on the micro-level in macro-urban network research. Taking Nanjing as an example, this study explores the characteristics of the network of the urban system from the perspective of people flow, refining the granularity of the analysis to the township- and street-level spatial units using mobile phone data. The findings are as follows: (1) There is a multicenter layered network pattern, with the main urban area being the core of the network, while Dongshan Street and Moling Street, as secondary centers, form a joint development pattern with the main urban area. (2) The spatial differentiation is significant. The spatial heterogeneity of "centralization in the central region, delayering in the north, and hierarchization in the south" is obvious. The net people inflow nodes are mainly concentrated in the main urban area and its surroundings, while the net outflow nodes are mostly located on the edge of the city. Moreover, the nodes to the south of Yangtze River are advantageous in urban resource control. (3) The phenomenon of "double shadow circle" appears in the ring of the main city and the ring of the municipal area. Moreover, the northern district experiences a serious outflow of population. (4) The effect of policy intervention is beginning to show. Improved levels of development of street and township units such as Jiangbei New District show the positive influence of national strategy on regional development.

Keywords: the space of flows; urban system; people flow; urban network analysis; Nanjing City

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1. Introduction

With the acceleration of the regionalization, the integration of information technologies and the comprehensive transportation system deepens. Meanwhile, the fluidity of the people flow, logistics, the information flow, the capital flow, and the technology flow between urban systems are significantly enhanced. Together, they prompted the transformation of the relationship between urban systems from the "local space" central place mode to the network mode based on "the space of flows" [1,2]. In the process of this transformation, their socioeconomic relations and spatial organization show delayered and networked characteristics, forming a network association system between towns and cities of different levels, scales, and properties [3]. Within this complex system, organic links are formed between towns through factor flows. The closeness of the factor links is directly related to the network degree. Factor flows not only strengthened the links between cities and towns, promoting their network development, but also facilitated the distribution of work and the integration of city and town functions, enhancing the overall effectiveness and operational efficiency of city and town networks. At the new stage of promoting regional coordination and high-quality development, it is of great significance to conduct an in-depth analysis of the characteristics of the spatial network patterns under the perspective of urban factor flows to reveal the interaction between towns and cities and the pattern of people flow, which may optimize the network structure of the urban system, promote the rational allocation of urban resources and synergistic development, and realize the high-quality development of urban factor flows and functional complementarity.

The network relationship of an urban system has always been a heated topic in academic research. From central place theory to the flow space, world city, and global city network, theoretical models of urban system research have been constantly evolving. The central place theory is the classic theory and method for early research on urban systems, which originated from Christaller's experimental research on market centers and service ranges of rural settlements in the 1930s. Using a deductive method, this research comes to the conclusion of a central place distribution model based on a hexagonal market area, which has been continuously improved to form the spatial distribution theory with scale hierarchy distribution as the core content and the system of spatial linkage measurement method of center towns based on the gravity model [4–7]. However, with the rapid development of globalization and informatization, the coexistence of the local space and the flow space has prompted the territorial spatial structure to shift from a hierarchical state to a networked state. As a result, the center place theory based on the attributes of place has, to a certain extent, shown maladaptation in the application of the theory and practice, demonstrating obvious defects in terms of the initial over-idealization of hypothetical conditions, the pursuit of the geometric diagrammatic structural depiction, and the negligence of the dynamics of the development of the urban systems. Subsequently, the research paradigm based on the space of flows theory began to rise, for it reflects the interactions between towns and cities through the "flow" data [8–10]. It makes up for the shortcomings of the gravity model and provides a new perspective for revealing the real inter-town relationships. International scholars have conducted a great deal of exploration regarding theoretical and empirical research on urban networks, which can be broadly categorized into "world city networks" and "regional networks" according to their differences on spatial scales. World city network research focuses on the global city system [11–16]. For example, Taylor (2001) puts forward the "world city network" and "central flow" research framework, which complements the traditional theory of central place, aiming to establish a city network based on the intra-company links [11,12] through the investigation and measurement of the international links between the headquarters and branches of high-level productive service companies. Regional network research focuses on the connectivity characteristics between regional cities and the structural characteristics of the overall network based on different perspectives such as production enterprises, social culture, and aviation [17–26].

Chinese scholars focus on the regional-level city network with urban agglomerations or provinces as the research area. They tend to quantify the urban network through the analysis of the flow of people, enterprises, organizations, infrastructure, information, etc. [27–32]. In recent years, with the development of mobile positioning technology, researchers began to use mobile phone data to measure the factor flows within the city. For example, Niu Xinyi et al. (2019) summarized the technical framework supporting the urban system planning based on mobile phone data. This framework includes four aspects, the spatial structure of towns and cities, town hierarchy, central city hinterland, and regional transportation facilities [33]. Similarly, Chen Yilin et al. (2020) used mobile phone data to analyze the human travel links between towns in the Chongqing urban system based on the dominant flow, town center hinterland, and radiation range, reflecting the hierarchical structure of the urban system and the characteristics of the network system [34]. Zhang Yang et al. (2021) used mobile phone data to identify the county–town hierarchical scale and spatial structure from the aspects of contact flow quantity and direction, evaluating its urban system comprehensively [35]. Based on the "three structures" of the urban system, Yu Yan et al. (2024) constructed a framework for measuring the structure of the urban system from the perspective of the space of flows using mobile phone data [36], conducting empirical studies in Ningbo City.

In summary, scholars have widely explored the urban system network, which has strong theoretical and practical significance. However, there are still limitations. First, as existing studies based on the data of people flow, information, enterprises, and other mobility links can only be conducted at the municipal level, it is difficult to reflect the links at lower township levels. Since mobile phone data can reach towns and even smaller spatial units, what are the characteristics on the micro-level of the space of flows in terms of structure and operation between towns? Are they different from those at the macro-level of the provincial and municipal domains? Second, considering the research on an urban system based on mobile phone data, although it uses dominant flow and attraction to analyze the urban system, it is still insufficient in the portrayal of detailed features such as the inter-node relationship, flow direction, and spatial organization structure. How can we refine the portrayal of the urban system network from a multidimensional perspective?

In response to the above, this paper aims to delve into the urban network pattern, flow direction, and network nodes from the perspective of people flow using the method of social network analysis. Dynamic and real-time mobile phone data will be used to analyze the spatial unit of towns and streets in Nanjing. Through in-depth analysis of the interaction mode, contact structure, and development pattern between towns, it aims to present the trends of factor flow, functional complementarity, and integration of urban internal networks, providing a theoretical basis for the study of Nanjing's urban development strategy. At the same time, the macro-urban network research is supplemented from the meso- and micro-scales. This makes up for the deficiency of the micro-research of the intra-urban network in mobile network research, further improving the theoretical system of the urban system network. The remaining part of this article is organized as follows: the second part describes the research area, research data, and research methods; the third part presents the major findings; the fourth part presents the discussion and policy recommendations; and the fifth part concludes the paper.

2. Material and Methods

2.1. Overview of the Research Area

This study selects Nanjing as the target area (Figure 1). Situated in the focal point of the Yangtze River Delta integration strategy, Nanjing occupies an important regional strategic position. Nanjing has 11 administrative districts. Except for the districts in the central urban area, three districts, Luhe, Lishui, and Gaochun, are also included, which have been transformed from individual counties, providing mature conditions for the study of the urban system. Since the focus of this study is to explore the spatial connection network of the town system and to reveal the overall characteristics of the urban system network in Nanjing and its influencing mechanism, this study chooses the main urban area of Nanjing, widely recognized by academia to be mature and developed, as the target area of research. For the areas outside this region, the study takes the towns and streets as the basic research units. These units include 59 towns and streets and one special unit of Laoshan Forest Farm to obtain more detailed and comprehensive research results.

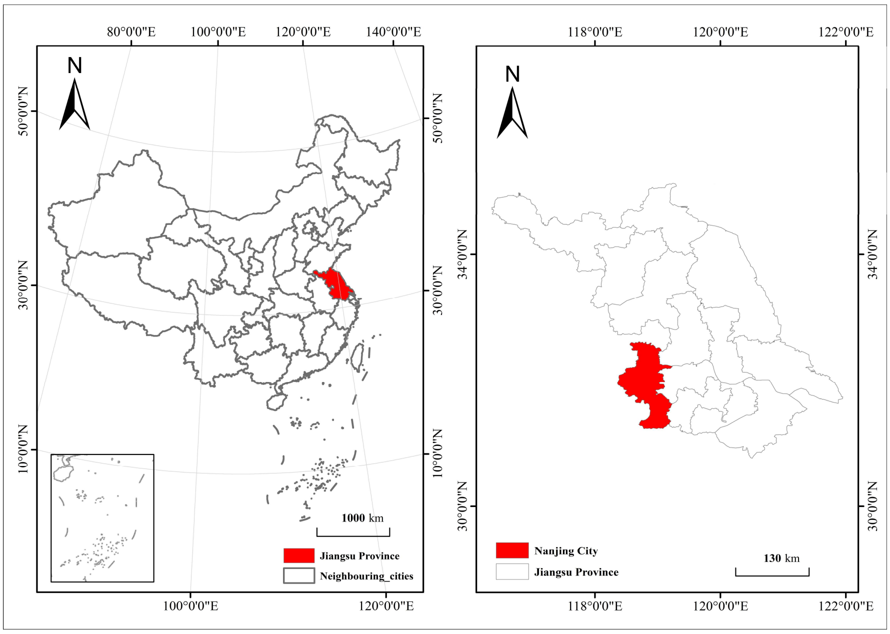

Figure 1. Nanjing, China.

2.2. Data Sources

The data used in this study come from the mobile phone data on China Unicom's "Smart Footprint" platform. Compared with traditional census data and urban network data, mobile phone data records the spatial location with the positioning of communication base stations, which covers a much smaller spatial scope than the general administrative boundaries of towns and streets. Therefore, these data are characterized as being relatively continuous and passive when recording the spatial behavioral characteristics of the mobile phone users' trajectories, making it possible to measure the real flow of people between towns and the urban area.

In order to obtain refined people flow statistics, this study divides Nanjing city into 26,349 grids of 500 $\times$ 500 m as the basic unit of analysis. In data processing, this study utilizes the regularity characteristics of mobile phone data with reference to existing research methods [37–40], combining the two major characteristics of user travel time and space to identify the usual place of residence, destination, and location of the user. The place where the user frequents the most and stays the longest at night (from 23:00 to 5:00 the next day) for 30 consecutive days is defined as the usual place of residence, which constitutes the starting point of the trip; whereas the location where the user stays the longest during the day (consider that economic or leisure activities take place) is seen as the destination, an ending point of the trip. By recording the number of trips and the corresponding number and frequency of contacts across regional spatial units and performing spatial matching of grids and locations, the OD flow model for the travel patterns of residents across districts is established. When performing spatial matching, for the grids whose origin and destination are both located entirely within a single town or street, we directly match them with the corresponding town or node unit. For the inter-grid flows located at the boundaries of towns and streets, this study adopts a refined matching method. Space is allocated proportionately according to the ratio of the corresponding town or street intersection area that the grid occupied, which significantly improves the accuracy of the people flow statistics. Through this method, this study successfully identifies a total of 21,384,455 inter-town trips within the 30 days of June 2019, which helps to construct a network model of people flow in the Nanjing urban system.

2.3. Research Methods

Social Network Analysis (SNA) focuses on the analysis of relationships. It presents the structural characteristics of the network comprehensively through a series of quantitative indicators, including the cohesive subgroups of the network, the centrality of the nodes, and the strength of the connections, etc. [41,42] Based on the existing research on urban systems that use mobile phone data, it focuses on using dominant flow analysis and attraction analysis to portray the structure of urban systems; however, the portrayal of detailed features such as the relationship between nodes, the direction of flow, and the spatial organization structure is still insufficient. This study combines the dynamic real-time mobile phone data and the relevant indicators of SNA with the basis of previous studies to concentrate the research unit from the macro-level of the whole country or provinces to the town or street unit. It comprehensively utilizes and combines a series of relevant indicators of SNA, conducting a combined analysis and in-depth research on the network pattern, flow direction, network nodes, and other multidimensional perspectives of town and street networks from the perspective of people flow, in order to explore the linkage pattern and interaction pattern of urban systems at the current stage.

(1) Cohesive subgroup

Cohesive subgroup analysis is used to explore the phenomenon of small group gatherings at each node in the Nanjing urban system and to identify the community structure and local network characteristics in the network based on the intensity of people flow connections between units. A total of 61 directed people flow networks between the main urban area of Nanjing and the surrounding towns and streets are transformed into a 61*61 matrix. Using the concor algorithm in Unicet 6.212, the pattern of cohesive subgroups of the urban system of Nanjing is analyzed, as well as the densities of each subgroup.

(2) Dominant flow

The dominant flow calculates the linkage flows between units and the number of higher flows that each attraction unit gathered from other units to reveal the linkage pattern between the main urban area of Nanjing City and the neighboring towns and streets. In the specific study, the first, second, and third major dominant flows are calculated, and the direction and scope of the flow of people between the main urban area of Nanjing and the surrounding towns and streets are determined by the maximum dominant flow.

(3) Correlation direction index

The correlation direction index is used to represent the direction of people flow between unit nodes. This index is used in this study to analyze the relative relationship between people inflow and outflow from nodes in the urban system, which helps to analyze the micro-function of town nodes in the network. The correlation direction index is categorized into six levels. A negative value means that the node has inflow. The lower the value is, the stronger the attraction ability it has. A positive value means that the node has outflow. The higher the value is, the more serious the outflow is. The formula for the correlation direction index is as follows:

$$D = \frac{O_i - I_i}{R_i}$$

In this formula, D represents the directional index; O_i represents the "out degree", namely the outflow of people; I_i represents the "in degree", namely the inflow of people; and R_i represents the total connectivity, namely the total amount of flow of people passing through the node.

(4) Node centrality

Node centrality reflects the ability of nodes to cluster and radiate in the network and is used to measure the importance of nodes. According to the difference in technological methods, centrality can be divided into degree centrality, closeness centrality, and betweenness centrality. In this study, degree centrality is used to measure the total number of people flow connections between nodes. Closeness centrality is used to measure the closeness of nodes to other network nodes. Betweenness centrality is used to measure the mediating and controlling functions of nodes in the whole network.

(5) Node affiliation

The degree of the node affiliation reflects the proportion that the people flow connections took up in the node. It is used in this study as an important indicator of the nodes' overall network flow patterns and linkage patterns. It calculated using the following formula.

$$r_i = \sum_{j=1}^{n} \frac{R_{ij}}{R_i}$$

Here, R_{ij} represents the degree of people flow connection between regions i and j and r_{ij} represents the degree of people affiliation.

3. Results

In this section, the results are analyzed from the macro-level to the micro-level and from general to specific regions, studying the "surface", "line", and "dot" of the urban system. The surface mainly refers to the state and form exhibited by the overall structure of the urban system network and its substructure, including the analysis of the overall and local network pattern; the line mainly refers to the flow of people between the nodes, including the analysis of the overall flow direction and that concerning the sub-nodes; and the dot mainly refers to the towns and streets in the urban system, including the total amount of people flow in the nodes, the connection between the nodes, and the analysis of the node's importance in the network.

3.1. "Surface": Overall Network Analysis

3.1.1. Overall Network Structure

(1) There is a central flow pattern with one main layer and multiple subordinate layers. Concerning regional development, an obvious difference between northern and southern flow patterns is evident.

The people flow network of the Nanjing urban system shows a flow pattern in which the centers of multiple layers are closely connected with their neighboring units. The main urban center and the district centers collaborate to promote the overall network development. The affiliation analysis (Figure 2) shows that the main urban area and the Liuhe sub-city (Xiongzhou Street, Liuhe District), the Lishui sub-city (Yongyang Street, Lishui District), and the Gaochun sub-city (Chunxi Street, Gaochun District) constitute the two-level development pattern with main and sub-city centers. The flow of people occurs mainly between geographically adjacent nodes, while the connection between distant nodes is relatively weak. The main urban area occupies a significant advantage in terms of the affiliation linkage, which highlights its cardinal role in the urban system, especially its strong ability to radiate and gather people flow to the neighboring streets and towns.

The pattern of the space of flows network presents the characteristic of "centralization in the central region, delayering in the north, and hierarchization in the south". Jiangning and Jiangpu Districts are geographically close to the main urban area, showing a strong affiliation and forming a centralized connection pattern with the center of the "central metropolitan area". The north and south districts of the city formed their own localized networks, respectively. While Lishui and Gaochun Districts in the south show a unidirectional linkage pattern of hierarchization within the district, Jiangbei New District in the north shows the coordinated development pattern of a multi-center network. As a national new district, Jiangbei New District provides both spatial and functional impetus for the development of the surrounding areas. "Xiongzhou-Ma'an-Longchi" and "Getang-Dafang-Pancheng" show characteristics of two-way connection and cluster development.

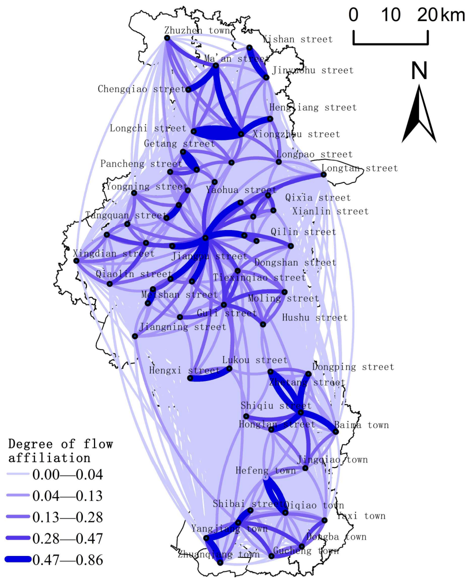

Figure 2. Network structure of people flow affiliation in the Nanjing urban system.

(2) The functions of suburban areas are integrated with that of the main urban area, and the phenomenon of "isolated islands" of people flow connection appeared in some areas.

The main urban area and its surrounding Dongshan and Moling Streets are the areas with the most frequent people flow, forming the "central core" of the connectivity network (Figure 3). In particular, Moling Street and Dongshan Street in Jiangning District, which are close to the south side of the main city, have extremely close connections with the main urban area. This indicates that the functional territory of the main urban area of Nanjing has expanded to the south and that Jiangning District, as a former suburb, has started its integration into the development of the main urban area. This integration allows Jiangning District to attract high-end talent, innovation resources, and advanced technologies from the main urban area, which promotes the leapfrog upgrade of the region's comprehensive strength. At the same time, the land, ecology, and tourism resources in Jiangning District are complementary to the main urban area, which jointly promotes their reciprocal development path.

There is still the phenomenon of "isolated island" when considering people flow in some areas, including Zhuzhen Town, Longzhao Street in Liuhe District, and Xingdian Street in Pukou District. In addition, some areas on the southern edge of the city, including Baima Street, Jingqiao Street, Yaxi Town, Dongba Town, and Gucheng Town, do not have much outflow of people. They constitute isolated areas lacking people flow. This phenomenon reflects the fact that there are still geographic constraints and urban–rural boundaries in Nanjing in terms of people flow. The correlation of people flow mainly occurs between geographically neighboring nodes, while the linkage between distant units is relatively weak. The insufficient integration and interaction between the peripheral areas of the city and the overall network indicates that Nanjing still has room for improvement in promoting coordinated development to achieving systematic, networked, and distinctive high-quality development.

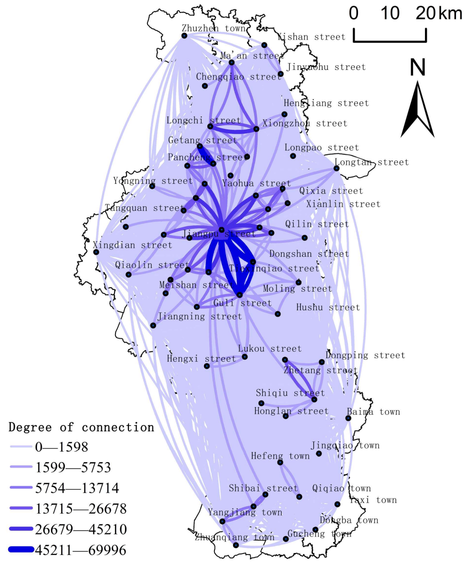

Figure 3. Network structure diagram of the connection degree of people flow in the Nanjing urban system.

3.1.2. Local Network Pattern

(1) The cross-river linkage network pattern around the main city started to appear and the economic phenomenon concerning administrative districts, namely, regions being transformed from county to district, is still obvious.

The pattern of the cross-river linkage of the people flow network around the main urban area has emerged. The cohesive subgroups analysis shows that Nanjing formed four primary subgroups and eight secondary subgroups (Figure 4). These subgroups are mainly distributed vertically from north to south, which reflects the principle of geographical proximity. It is important to note that subgroup I in the central area surrounding the main urban area includes the entire area of the main urban area, Jiangbei New District, Yuhua District, Qixia District, and some streets in Pukou District, Liuhe District, and Jiangning District, forming an organic and dynamic spatial pattern, which spatially straddles the Yangtze River and surrounds the main urban area. This phenomenon suggests that the flow of people has, to a certain extent, transcended the limitations of administrative divisions and the Yangtze River barrier. It manifests the mobile characteristic of the interaction between diverse spaces. The cross-river linkage pattern around the main urban area not only promotes the interaction of people flow within the region but also strengthens the connection between the local districts and the main urban area. This cross-river linkage network pattern of people flow provides a new impetus for the integrated development of urban and rural areas in Nanjing, which helps to promote the sharing of resources and the functional complementation between regions.

In some areas, the economic phenomenon concerning administrative districts, namely, regions being transformed from county to district, is still obvious, and urban-rural barriers still exist. The analysis of the internal density of the secondary subgroups and the inter-subgroup density shows that subgroup No. 1, which contains the main urban area, has the highest average density with all other subgroups, indicating that this subgroup has strong people flow with any other district of Nanjing and that it occupies an important position as the core driving force in the current network of people flow. However, the subgroups No. 3 (containing Liuhe District), No. 5 and No. 6 (containing Lishui District), and No. 7 and No. 8 (containing Gaochun District), all show a high internal network density and a very low external network density, which reflects the relatively limited connection subject and range of these areas. This phenomenon reveals the historical problems left from the process of "transforming counties to districts" that Nanjing once conducted. Some districts are still in a relatively isolated development stage. The urban–rural barriers still exist. Neither has an integrated development pattern nor linkage across districts currently been formed.

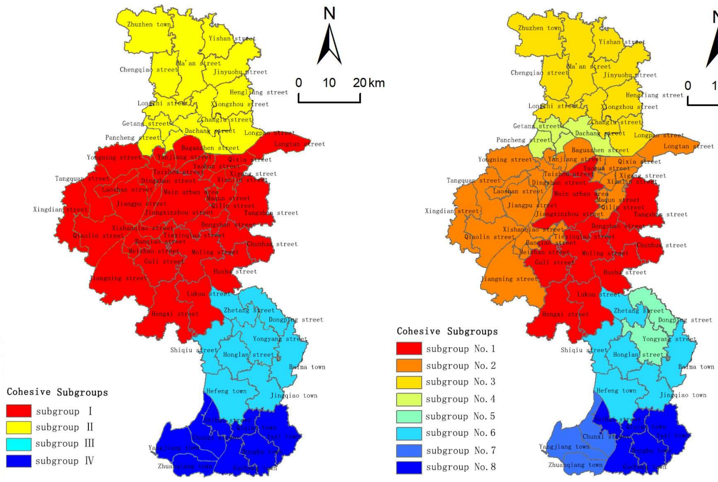

Figure 4. Spatial distribution map of cohesive subgroups of primary and secondary networks in the Nanjing urban system.

3.2. Line—Flow Direction Analysis

3.2.1. Overall Flow Direction

(1) Formation of a flow network with centralized vertical gradient linkages and horizontal "town clusters" and "urban-town pairs" linkages for Nanjing's people flow.

In the vertical dimension, the direction of people flow is mainly characterized by centralized gradient connections under hierarchical linkages, a feature that dominates the structure of the space of flow network. Through the analysis of dominant flows (Figure 5), the largest people flow usually goes to "neighboring centers", which reflects the hierarchical and vertical connection characteristics. For example, the main urban area, as the center, attracts the largest dominant flows from 19 surrounding towns and streets. Similarly, Yongyang Street, as the administrative center of Lishui District, gathers the most dominant flows of almost all towns and streets in the district. A further analysis of the second and third largest dominant flows shows that the characteristics of centralized flow are evident in every district. This means that the areas with the most frequent interaction of people flow are the units with administrative jurisdictional relationship and geographic proximity and that administrative forces and zoning factors exert a fundamental influence on the network structure of the urban system.

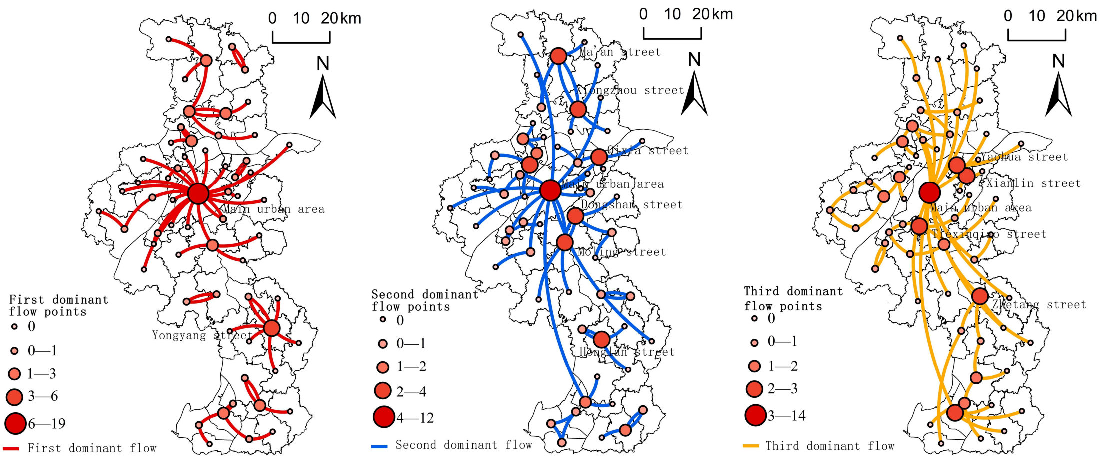

Figure 5. Flow direction map of dominant flow in the Nanjing urban system.

In the horizontal dimension, the direction of people flow started to show a trend of horizontal cooperation and connection, with the initial formation of mobile networks of "town agglomerations" and "urban-town pairs". This reflects the very first breakthrough of the spatial structure of Nanjing under the centralized land model. Under the direct administration of Jiangbei New District, Ge Tang, Dafang, Pancheng, Yanjiang, Taishan, and other streets have formed a multi-unit group development pattern of "local micro-circulation". In Liuhe District, Ma'an, Xiongzhou, and Longchi Streets serve as the centers that connect surrounding towns and streets to form a diversified network with organic links. Comparatively, Pukou District has formed a ring pattern of "Jiangpu—Qiaolin—Xingdian—Tangquan—Laoshan Forestry", which closely connects multiple different units. These phenomena indicate that horizontal linkage networks based on functional complementarity have started to take shape in some regions. In addition, the town-to-town pair structure has emerged between geographically adjacent units. For example, Longchi–Xiongzhou, Tuotang–Yongyang, Hengxi–Lukou, Jinniu Lake–Yeshan, etc., respectively constitute each other's most dominant flow, forming remarkable town pairs.

(2) The main urban area of Nanjing has become a "highland" for attracting people and the phenomenon of "double shadow circle" has appeared around the main urban area and the municipal area.

Analysis of the directional index reveals (Figure 6) that the main urban area has the lowest directional index of -0.17. It indicates that the main urban area is extremely attractive to the flow of people, having a significantly higher agglomeration function than radiation function. In addition, the directional index of Changlu Street, Qixia Street, Yaohua Street, and other units surrounding the main urban area is also at a low level, indicating that these areas also play the role of agglomeration with their net people inflow. Because of their advantages in employment opportunities, public services, and infrastructures, the main urban area and its neighboring areas became the "highland" for attracting people. As a result, the centralized flow became the main flow direction of the urban system in Nanjing.

There is a "double shadow circle" around the main urban area and the municipal area. People outflow is serious in the northern areas, with typical examples of Taishan Street and Yanjiang Street, which are known as the "siphoning" areas of the main urban area (Figure 7). The amount of people flowing out of these areas to the main urban area is at the highest level, which leads to a large number of cross-river flows. This kind of "double shadow circle" spatial structure reflects the siphoning effect of the main urban area. It also reveals the combined impacts that spatial distance, economic development, employment opportunities, and level of infrastructure and public services exert on the people flow. The study also found that the problem of people outflow is more serious in the northern area. This phenomenon suggests that, in the process of promoting coordinated regional development, special attention and measures need to be taken to alleviate the population loss in the northern part of the region to promote balanced internal development.

(3) Existence of the mapping relationship between "value sequences" and the urban development stage and model.

The value sequences of different areas reflect their respective developmental stages and modes. It shows the dynamic and processual nature of urban–town integration. The towns and streets surrounding the main urban area show a strong tendency to move centrally towards the main urban area, forming a development pattern of "strong main urban center and weak local centers". Under this pattern, the surrounding areas can fully utilize the development radiation of the main urban area, such as employment opportunities, high-quality education, and medical resources. However, the absolute dominance of the main city center may also limit the development of the functions of local centers in serving their own areas.

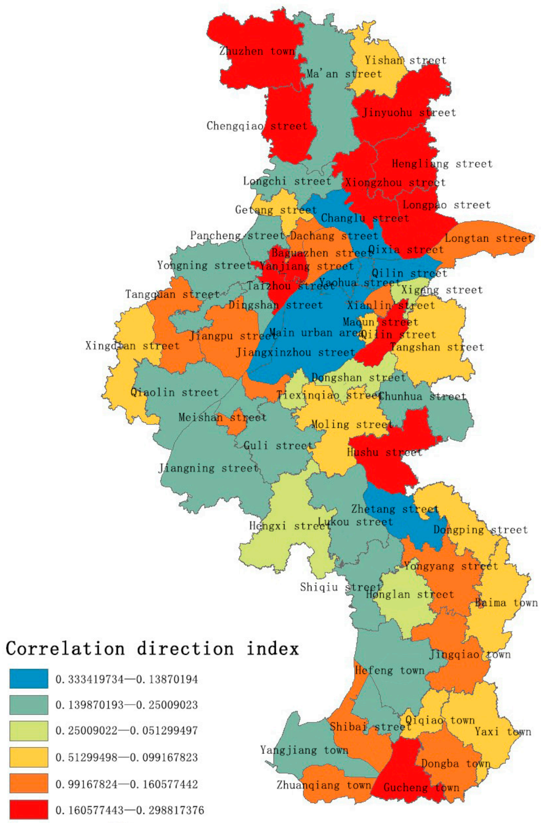

Figure 6. Spatial distribution map of correlation direction index in the Nanjing urban system.

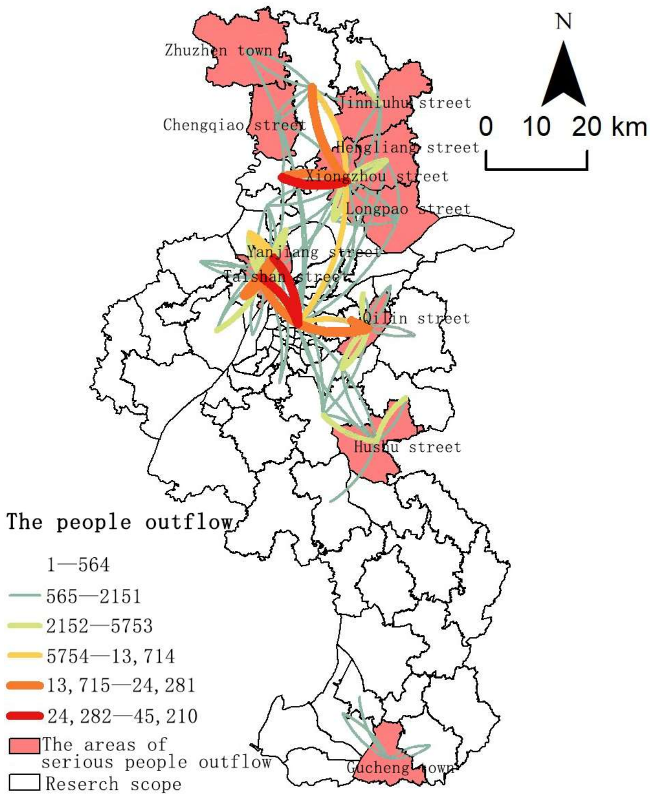

Figure 7. Flow direction map of people in areas with serious people loss in Nanjing.

In addition, this study found that Lishui District, located in the southernmost part of Nanjing, represents a "strong local center" pattern, in which the greatest dominant flow of 85.7% of the towns and streets flow to the administrative center of the district, Yongyang Street. This pattern shows the dominant role and strong attraction of local centers in promoting "local urbanization" and local economic prosperity. Nonetheless, the single-center development pattern may reduce high-quality interactions between towns and the main urban area in terms of culture, technology, and talent. Gaochun and Liuhe Districts, at the southern and northern ends of the city, respectively, show a pattern that gives priority to "proximate connections", reflecting the more isolated developmental nature of these districts. These districts are currently at the initial stages of network development. The leading roles of neither the local centers nor the main urban area are fully exerted, resulting in a relatively fragmented and disordered development status.

3.2.2. Meso-Analysis of the Direction of Flow of Sub-Nodes

In order to conduct an in-depth exploration of the characteristics of the people flow network in urban systems, this study conducts a meso-analysis of the sub-nodes, paying particular attention to the network functions and hierarchical characteristics of "three sub-cities" and "nine satellite cities" to reveal their network development trend at this stage.

(1) Three sub-cities present the parallel development model.

The three sub-cities share the role of linking themselves with the main urban area and radiating the town and streets within their respective areas in terms of people flow connection (Figures 8 and 9). The connection intensity between the sub-city centers and the main urban area is proportional to their spatial distance from the city. For example, Liuhe sub-city has the largest people flow to the main city, followed by Lishui sub-city. However, Gaochun sub-city, having the farthest distance to the city center, has relatively smaller people flow to the main city. The connection between the sub-cities and the main urban area is asymmetric. For example, the people flow from Liuhe sub-city to the main urban area belongs to the fourth level (5254–13.125), while the people flow from the main urban area to Liuhe sub-city is only at the second level (544–2231). This means that the siphoning effect exists and that sub-city centers close to the main urban area are the subject of siphoning in terms of people flow factors. The two-way reciprocal development pattern has not yet formed.

Around both Liuhe sub-city and Lishui sub-city, "strong" unit nodes that form a stable two-way flow with the center of the sub-cities have appeared. For example, a large people flow between Liuhe sub-city and Longchi Street or Ma'an Street exist. Strong connections between Lishui sub-city and Zhetang Street are also evident. This may be caused by the good employment conditions provided by the surrounding towns and streets, which are able to attract a large number of commuters. Under the background of the strong development of the main urban area, the sub-city centers need to integrate the advantages of their surrounding unit nodes, transforming from individual competition to team cooperation to promote the transformation and upgrading of the whole area.

(2) Nine satellite cities present polarized and balanced development patterns, lacking horizontal cooperation.

The urban areas of the nine satellite cities show differentiated development trends that can be divided into balanced and polarized patterns according to the people flow direction patterns (Figures 10 and 11, Table 1). Districts that follow the balanced pattern, such as Qiaolin satellite city and Lukou satellite city, maintain diversified connections with various nodes of the urban system. They undertake the roles of unique functional nodes in each district. Districts following the polarized pattern, on the other hand, are closely connected to the main urban areas or the centers of sub-cities and have fewer connections to other nodes. They show strong polarized central connection characteristics. Some typical examples are Banqiao satellite city, Binjiang satellite city, and Lukou satellite city. Satellite cities lack connections between them, even for the new city pairs with adjacent geographical locations and supporting industrial functions, such as Longtan satellite city and Longbao satellite city, where people flow connections are still extremely limited. This indicates that although the vertical hierarchical network connection of the urban system is strong, there are obstacles to the flow of people between nodes of the same size and level. A stable network of diversified organic connection has not yet been formed and the cooperation and communication between satellite cities need to be further strengthened.

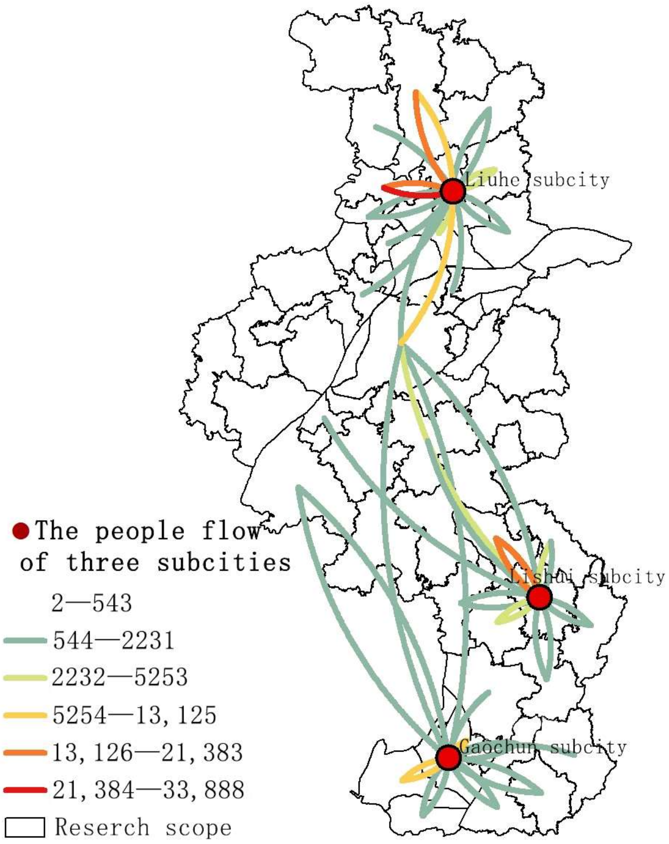

Figure 8. Comprehensive structure diagram of the people flow network of "three sub-cities" in Nanjing.

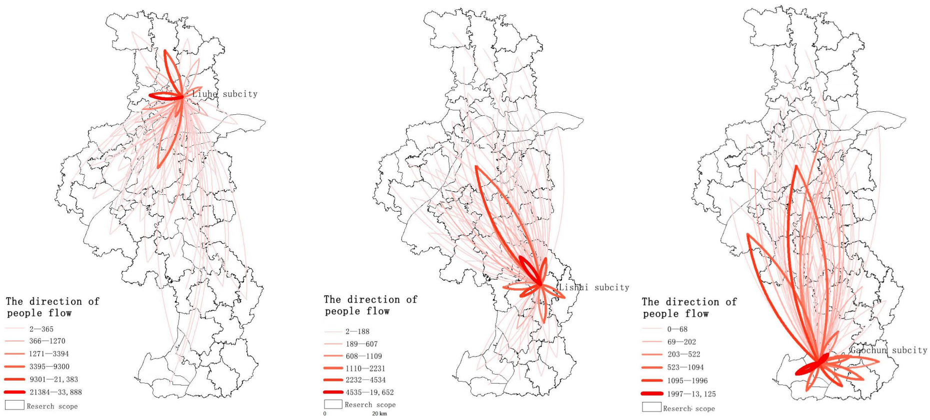

Figure 9. The map of people flow network structure of "three sub-cities" in the Nanjing urban system.

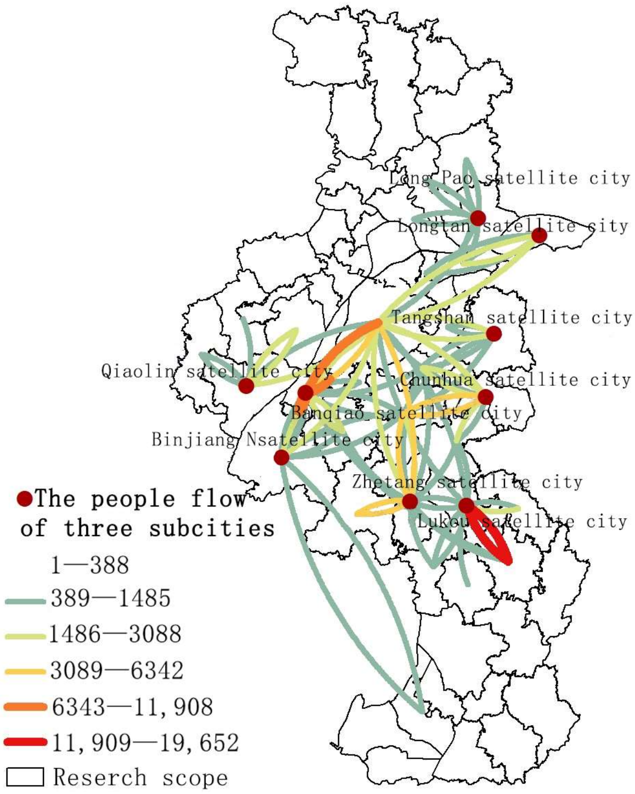

Figure 10. Comprehensive Map of people flow network structure in "nine satellite cities" in Nanjing.

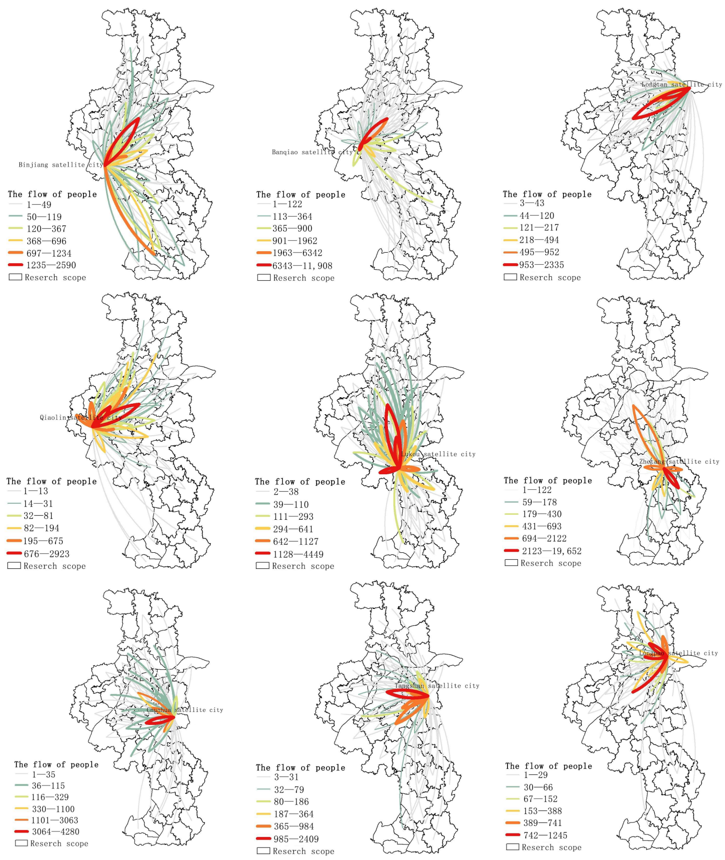

Figure 11. Structure diagram of the people flow network of "nine satellite cities" in the Nanjing urban system.

Table 1. Table of the people flow pattern of "nine satellite cities" in the Nanjing urban system.

The Polarized Patterns	Binjiang satellite city	Enclave linkage pattern, with network gaining initial significance
	Banqiao satellite city	Main-city-oriented linkage pattern with significant polarization
	Longtan satellite city	Axial linkages and single pattern of inward linkages
The Balanced Patterns	Qiaolin satellite city	Fan-like balanced linkage pattern, new growth pole pattern formed
	Lukou satellite city	Diverse and dense connectivity pattern, reflecting a distinctive gateway hub characteristic
	Zhetang satellite city	Clear administrative orientation, with strong ties to neighboring areas
	Chunhua satellite city	Multiple attractive linkage patterns
	Tangshan satellite city	A triangular pattern of solid linkages that enhances the stability and sustainability of urban–rural integration
	Long Paog satellite city	Peripheral outflow connection pattern
	Lishui subcity	Diversified and dense connectivity pattern, with strong links to neighboring areas and the main city area.
	Liuhe subcity	A solid triangular linkage pattern with strong connections to neighboring areas.
	Gaochun subcity	A fan-like pattern of balanced connections to neighboring areas and the main city area.

3.3. *Dots—Network Nodes*

3.3.1. An Obvious Hierarchy and Polarization Trend Exist in Network Nodes

The main urban area occupies the first level in Nanjing's people flow network (Figure 12) and has a solid core position. Dongshan and Moling Streets are at the second level, having formed a cooperative development pattern with the main urban area as the core and neighboring towns and streets as participants. Xiongzhou, Longchi, Getang, Dafang, and Taishan Streets in Jiangbei New District are in the third and fourth levels, constituting a town belt with strong interactive capacity. Most of the streets and towns in Jiangbei New District occupy this level, which reflects the promotional effect of the national strategy on the development of regional town and street units. It demonstrates the powerful intervention of policies on the development of the area. The fifth level units, such as Ma'an, Lukou, Zhetang Streets, etc., are located on the north–south axis of Nanjing, which shows that the centrality of the network nodes is strongly influenced by the geographic location. The lowest level units, such as Jingqiao, Yaxi Town, Zhuzhen Town, and Xindian Street, have a 20-fold difference in the centrality of people flow with the first two levels, which indicates a significant polarization trend.

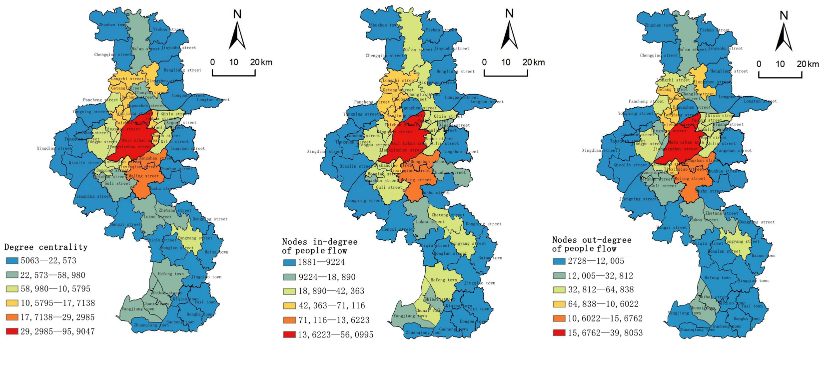

Figure 12. Spatial layout of the node centrality of the Nanjing urban system.

3.3.2. Spatial Differentiation Characteristics of the Inflow and Outflow Pattern of Network Nodes

The inflow–outflow pattern of network nodes shows obvious spatial differentiation characteristics (Figures 12 and 13). The people flow at the town and street levels can be divided into three categories. The first category is the net inflow nodes, such as the main urban area and the core location units such as Changlu Street, Yaohua Street, and Jiangxinzhou Street. The second category is the nodes with relatively balanced inflow and outflow, which are economically inactive units on the edge of the city, such as Jingqiao Town, Xingdian Street, and Yaxi Town. The third category is the net outflow nodes, such as Xiongzhou, Taishan, Yongyang, Jiangpu, Dongshan, etc. The sub-centers, such as Xiongzhou and Yongyang Street, act as "mediators", attracting people inflow from the surrounding towns and streets. However, a large number of residents still flow to the main urban area, forming a gradient flow pattern of "ordinary unit → district centers → main city center", which reflects the condition of the secondary nodes in the urban system network that do not have a large enough people inflow to cover the outflow.

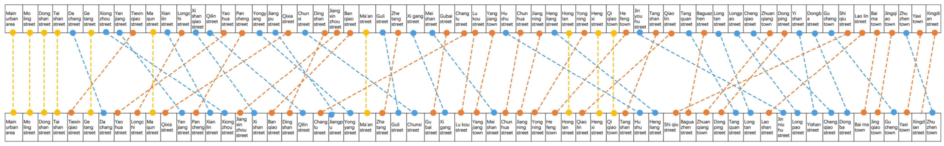

Figure 13. Comparison chart of node in-degree and out-degree in the Nanjing urban system.

3.3.3. The Network Node Linkage Pattern Follows a "Northwest-Southeast" Direction, with Spatial Differentiation between the Intermediary Nodes in the Northern and Southern Part of Yangtze River

The development pattern of Nanjing's town nodes follows the "northwest-southeast" direction of Jiangbei New District—main urban area—Dongshan, Moling, and Lukou in Jiangning District (Figure 14). It coincides with the basic structure of the people flow, which indicates that the nodes on this axis are the most closely connected in the network of the urban system in terms of people flow.

The nodes that have the roles of "mediator" in the urban system network are spatially differentiated in the south and north areas of the Yangtze River. Nodes in the south dominate the urban and rural resources (Figure 14). Units with a high degree of betweenness centrality are mainly clustered in the south of the main urban area, such as the main urban area, Dongshan Street, Moling Street, Lukou Street, etc. They constitute the city's important people flow hub. The second level of units is concentrated around the main urban area, including the administrative centers of the districts such as Yongyang Street and Chunxi Street. They exert a great impact on the people flow network in the region. The street nodes of Jiangbei New District are mainly located at the third level, which is spatially different from the development trend of the south of the river. The intermediary position of Jiangbei New District nodes in the Nanjing urban system network is still not significant, showing endogenous development characteristics.

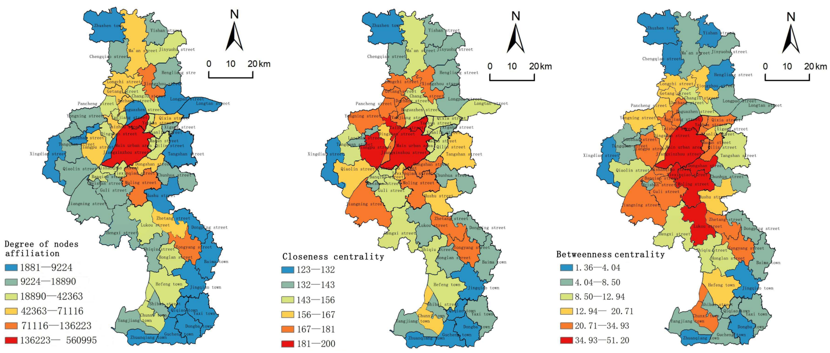

Figure 14. Spatial layout of node centrality in the Nanjing urban system.

4. Discussion and Conclusions

4.1. Discussion

Under the wave of globalization and informatization, towns and cities are closely connected by physical transportation systems and virtual information systems, as well as by the flow of human, material, financial, and information elements. The mobility attribute of the urban system network is constantly increasing. Compared with the existing research on the urban system, this study, on the basis of reviewing the related research on urban system network, focuses on the spatial units at the town and street levels of Nanjing through the perspective of "the space of flows". It delves into the structure of the urban system, the flow direction, and the network nodes of Nanjing based on the people flow connection characteristics collected from mobile phone data, which further indicate the spatial connections in the urban network. The dominant flow, centrality, and cohesive subgroups in the social network analysis method are also applied. This study supplements the macro-level research on urban networks through the micro- and meso-angles that it provides, deepening the studies on the internal networks of the city and supplementing the "space of flows" theory. At the same time, it quantitatively analyzes the pattern of Nanjing's urban system from a multi-dimensional perspective, which provides supporting data for urban distribution, the rational allocation of resources, and promoting coordinated urban development.

The results of this study show that the pattern of urban linkages is characterized by an obvious spatial hierarchy and geographic proximity. Intense people flow linkages generally occur in the vicinity of the core nodes and between geographically adjacent towns. The centrality of the main urban area is extremely prominent, a finding also confirmed by other related studies [35,36,39,43]. Whether at the macro-level, such as the Yangtze River Delta, or at the micro-level of cities and counties, it is found that the pattern of the urban system under the perspective of human flow is affected by the geographic location and the administrative level of the nodes. The central urban area occupies the dominant position in the structure of urban–town connections, the towns around the urban area frequently interact with the urban area by virtue of their geographical advantages and the peripheral zones often have the status of having a net outflow of people. Meanwhile, this study finds that the deconstruction and remodeling of local space caused by the space of flows goes simultaneously with the "district economy" as a dual track. This is mainly reflected in the fact that people flow in Nanjing has somewhat transcended the limitations of administrative divisions and the Yangtze River barrier. However, the pattern that factor flows are divided by districts is still obvious. This phenomenon shows that Nanjing's development is at a stage of transition between the old and the new, influenced by both multiple complex and open factor flows and the constraints of traditional zoning forces, which is reflected in the spatial pattern of factor flows of "centralization in the central region, delayering in the north, and hierarchization in the south" in each district. This further proves the theoretical viewpoint that the space of flows and the space of place jointly shape the structure of an urban system [8,9], providing corresponding empirical evidence and data support. Optimization ideas for upgrading the spatial structure of the urban system and guiding the reasonable flow of the urban factor are provided as well.

In addition, the results of the analysis of the sub-nodes of the three sub-cities and the nine satellite cities show that there are obstacles to people flow between nodes of the same scale and level. Horizontal connections among the nine satellite cities are relatively lacking, and a stable network of diversified organic connection is not yet formed. Therefore, they can learn from the development model of "relying on partners" that the three sub-cities adopted, effectively integrating the advantages of multiple nodes to shift from individual competition to team cooperation. These regions need to focus on cultivating the distinctive regional functions, enhance the radiation effect that facilitates the development of their surrounding areas, and, in particular, enhance the ability to attract people. Meanwhile, they need to gain popularity through improving the quality and cultural atmosphere of their regions and develop into a regional center that is organically linked with the main urban area with complementary functions in order to promote the transformation and upgrading of the entire district and the balanced development of the multiple regional centers.

The limitation of this study is that it only considered the element of people flow, which does not fully reflect the spatial characteristics of the urban space of flows under the joint influences of multiple flows. Therefore, future research can add analyses of multiple factor flows, such as logistics, information flow, and capital flow, to obtain a more comprehensive understanding of the characteristics of the urban space of flows and to enhance the depth and practical value of the study.

4.2. Conclusions

Based on mobile phone data, this study adopts the social network analysis method to conduct in-depth exploration of the spatial pattern of the people flow network of the Nanjing urban system. It possesses several characteristics: (1) There is a multi-center layered network pattern. The people flow network in the Nanjing urban system shows an obvious hierarchical structure, in which the main urban area serves as the core of the network and has significant agglomeration and radiation functions. Dongshan and Moling Streets, as secondary centers, form a cooperative development pattern with the main urban area. (2) There is significant spatial differentiation. The people flow network in the Nanjing urban system shows the spatial heterogeneity of "centralization in the central region, delayering in the north, and hierarchization in the south". The inflow and outflow of the network nodes as well as the linkage pattern both show significant spatial differentiation characteristics. The net people inflow nodes are mainly concentrated in and around the main urban area, while the net outflow nodes are mostly located at the edge of the city. This indicates that the people outflow in some streets in the urban system network is stronger than the people inflow. In addition, the intermediary status of the network nodes is also spatially differentiated between the areas north and south of the Yangtze River, with the nodes south of the river having an advantage in the control of urban resources. (3) There is the phenomenon of a "double shadow circle". The main urban area and its neighboring units have become the "highland" for attracting people flow. However, the "double shadow circle" has appeared in the ring of the main urban area and the ring of the municipal area. The northern part of the city has a substantial people outflow, revealing the imbalance of regional people flow. (4) The effect of policy intervention is beginning to show. The improvement of the development level of town and street units such as Jiangbei New District shows the positive impact of the national strategy on regional development. Policy intervention has played a key role in promoting the development of regional town and street units. However, it should also be noted that the intermediary status of the Jiangbei New District nodes in the urban system network is still insignificant and needs to be further strengthened.

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References

1. Castells, M. Globalization, networking, urbanization: Reflections on the spatial dynamics of the information age. *Urban Stud.* **2010**, *47*, 2737–2745. [CrossRef]
2. Hall, P.; Pain, K. *The Polycentric Metropolis: Learning from Mega-City Regions in Europe*; Earthscan: London, UK, 2006.

3. Wu, K.; Fang, C.; Zhao, M. Spatial organization of Chinese city networks and their complexity structural characteristics. *Geogr. Res.* **2015**, *34*, 711–728.
4. Yan, W.; Wang, F.; Qin, Y. Evolution and mechanism of theoretical modeling of urban spatial interaction. *Adv. Geogr. Sci.* **2009**, *28*, 511–518.
5. Gu, Z.; Pang, H. Spatial connection and stratification of Chinese urban system based on gravity model. *Geogr. Res.* **2008**, *01*, 1–12.
6. Chen, R.; Wang, N.; Zhao, Y.; Zhou, Y. Complex network analysis of interprovincial mobile people based on improved gravity model. *China People·Resour. Environ.* **2014**, *24*, 104–113.
7. Li, C.; Jin, X. A study on the measurement of spatial linkage of center towns based on gravitational model—A case study of 25 center towns in Jinhua City, Zhejiang Province. *Geoscience* **2016**, *36*, 724–732.
8. Wang, S.; Lian, C.; Zhao, Z. From Centerlands to Urban Networks-A Theoretical Shift in the Study of China's Town System. *Geogr. Res.* **2019**, *38*, 64–74.
9. Hu, G.; Chen, C.; Jin, X.; Wang, Q. Research on the Networking of Urban system in China. *J. Geogr.* **2019**, *04*, 28–34.
10. Wang, Y.; Niu, X.; Song, X. Progress of Research on Regional Spatial Structure from the Perspective of "Flow Space". *Int. Urban Plan.* **2017**, *32*, 27–33. [CrossRef]
11. Taylor, P. Specification of the world city network. *Geogr. Anal.* **2001**, *33*, 181–194. [CrossRef]
12. Taylor, P. The new geography of global civil society: NGOs in the world city network. *Globalizations* **2004**, *1*, 265–277. [CrossRef]
13. Beaverstock, J.V. World-city network: A new metageography. *Ann. Assoc. Am. Geogr.* **2000**, *45*, 123–143. [CrossRef]
14. Derudder, B.; Taylor, P.J. Three Globalizations Shaping the Twenty-first Century: Understanding the New World Geography through Its Cities. *Ann. Am. Assoc. Geogr.* **2020**, *110*, 1831–1854. [CrossRef]
15. Derudder, B.; Witox, F. An Appraisal of the Use of Airline Data in Assessing the World City Network:A Research Note on Data. *Urban Stud.* **2005**, *42*, 2371–2388. [CrossRef]
16. Ou, Y.; Huang, G.; Chen, R.; Chen, H.; Xie, A.; Xue, D. From Western centralism to decentralization: Trends, breakthroughs and limitations in the world city network based on the winter olympic games. *Appl. Geography* **2024**, *164*, 103200. [CrossRef]
17. Camagni, R.; Salone, C. Network Urban Structures in northern Italy: Elements for a theoretical framework. *Urban Stud.* **1993**, *30*, 1053–1064. [CrossRef]
18. Grubesic, T.H.; O'Kelly, M.E. Using points of presence to measure accessibility to the commercial internet. *Prof. Geogr.* **2002**, *54*, 259–278. [CrossRef]
19. Mitchelson, R.L.; Wheeler, J.O. The flow of information in a global economy: The role of the American urban system in 1990. *Ann. Assoc. Am. Geogr.* **1994**, *35*, 87–107. [CrossRef]
20. Ratti, C.; Sobolevsky, S.; Calabrese, F.; Andris, C.; Reades, J.; Martino, M.; Claxton, R.; Strogatz, S.H. Redrawing the map of great Britain from a network of people interactions. *PLoS ONE* **2010**, *5*, e14248. [CrossRef]
21. Liu, X.; Gong, L.; Gong, Y.; Liu, Y. Revealing travel patterns and city structure with taxi trip data. *J. Transp. Geogr.* **2013**, *43*, 78–90. [CrossRef]
22. Lu, T.; Wu, Z.; Huang, L. Network Relationships and Spatial Organization:A Comparative Analysis of Innovation Partnerships between the Yangtze River Delta and the Northeastern U.S. City Clusters. *J. Urban Plan.* **2016**, *12*, 35–44.
23. Yang, H.; Dijst, M.; Witte, P.; Van Ginkel, H.; Yang, W. The spatial structure of high speed railways and urban networks in China: A flow approach. *Tijdschr. Voor Econ. En Soc. Geogr.* **2018**, *109*, 109–128. [CrossRef]
24. Mou, N.; Yuan, R.; Yang, T.; Zhang, H.; Tang, J.; Makkonen, T. Exploring spatio-temporal changes of city inbound tourism flow: The case of Shanghai, China. *Tour. Manag.* **2019**, *76*. [CrossRef]
25. Akhavan, M.; Ghiara, H.; Mariotti, I.; Sillig, C. Logistics global network connectivity and its determinants. A European City Network analysis. *J. Transp. Geogr.* **2020**, *82*, 102624. [CrossRef]
26. Shi, X.; Wu, J.; Wu, B.; Wang, K. Distribution characteristics and spatial conjugate relationship of heterogeneous tourist flows from the perspective of multiple transportation. *Sci. Geogr. Sin.* **2022**, *42*, 1546–1554.
27. Shen, L.; Xi, G.; Qin, X.; Wang, M. Spatial Characterization of Regional Mobility Based on Express Logistics Measurement-Taking Jiangsu Province as an Example. *Hum. Geogr.* **2018**, *33*, 102–108.
28. Sheng, K.; Yang, Y.; Sun, W. Influencing factors and formation mechanism of urban network centrality in China—Based on the network perspective of top 500 listed companies. *Adv. Geosci.* **2019**, *38*, 248–258.
29. Wang, J.; Jing, Y. Characteristics and Organization Patterns of Urban Network Hierarchy in China—A Comparison Based on Railway and Air Flow. *J. Geogr.* **2017**, *72*, 1508–1519.
30. Wang, B.; Zhen, F.; Xi, G.; Qian, Q.; Wu, C. A Study on Web Information Geography Based on Microblog User Relationships-Taking Sina Microblog as an Example. *Geogr. Res.* **2013**, *32*, 380–391.
31. Jiang, X.; Wang, S. Research on People Mobility Networks in Chinese Cities Above Prefecture Level--Analysis Based on Baidu Migration Big Data. *China People Sci.* **2017**, *41*, 35–46+127.
32. Tang, H.; Xu, W.; Wang, C. Study on the Centrality and Influencing Factors of Yangtze River Delta Urban Agglomeration Based on Information Flow. *Geogr. Geogr. Inf. Sci.* **2022**, *38*, 94–102.
33. Niu, X.; Kang, N.; Wang, Y.; Xie, Y. Technical Framework of mobile phong Data Supporting Urban system Planning. *Geogr. Inf. World* **2019**, *26*, 18–24.
34. Chen, Y.; Huang, M.; Tang, X. Study on the organizational characteristics and evaluation of the network structure of Chongqing mountain towns-from the perspective of mobile phone data. *Urban Archit.* **2020**, *17*, 11–14.

35. Zhang, Y.; Ma, N.; Guo, Y. Identification of county urban system based on mobile phone data-A case study of Poyang County, Jiangxi Province. *Reg. Res. Dev.* **2021**, *40*, 1881–1896.
36. Yu, Y.; Fan, J.; Gao, X.; He, Y.; Xu, Y. Measurement of urban architecture supported by mobile phone data-from the perspective of flow space. *J. Xi'an Univ. Archit. Technol. (Nat. Sci. Ed.)* **2024**, *56*, 2191–2202.
37. Ding, L.; Niu, X.; Song, X. Measurement of Employment Center system in Shanghai Central City—Research based on cell phone signaling data. *J. Geogr.* **2016**, *71*, 484–499.
38. Niu, X.; Ding, L.; Song, X. Identification of urban spatial structure of Shanghai central city based on mobile phone data. *J. Urban Plan.* **2014**, *11*, 61–67.
39. Niu, X.; Wang, Y.; Ding, L. Using mobile phone data to measure the hierarchical structure of urban system. *Planner* **2017**, *33*, 50–56.
40. Li, Z.; Zhen, F.; Huang, G.; Qin, X. Urban Centrality Measurement and Planning Application Based on Multi-source Data—Taking Changzhou as an Example. *J. Urban Plan.* **2019**, *11*, 111–118.
41. Liu, J. *Introduction to Social Network Analysis*; Social Science Literature Publishing House: Beijing, China, 2004; pp. 1–75.
42. Shen, L.; Wang, X.; Zhen, F. Characteristics of urban mobile spatial network from the perspective of social network analysis. *Urban Probl.* **2017**, *34*, 28–34.
43. Li, Z.; Sun, H.; Li, L. Analysis of intercity travel in the Yangtze River Delta based on mobile signaling data. *J. Tsinghua Univ. (Sci. Technol.)* **2022**, *62*, 1203–1211.