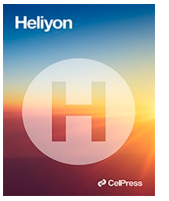
Heliyon 10 (2024) e30377

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon



Research article

Characteristics of urban network and city functions in the Yangtze River Delta Region: A multi-scale perspective

Shaohua Zhang [a], Jun Cai [a,*], Ye Wei [b], Qiyao Yang [a], Lemei Li [a]

[a] School of Architecture and Fine Art, Dalian University of Technology, Dalian, Liaoning, 116024, China
[b] Affiliations: Key Laboratory of Geographical Processes and Ecological Security in Changbai Mountains, Ministry of Education, School of Geographical Sciences, Northeast Normal University, Changchun, Jilin, 130024, China

ARTICLE INFO

Keywords:
Multi-scale
Urban network
Rescaling
City functions
Buzz and pipelines model

ABSTRACT

The development of cities and regions emerges from the complex associations at various spatial levels, highlighting the importance of a multi-scale approach to analyzing regional urban networks. This study attempts to establish a new analysis framework encompassing national, regional, and local dimensions by employing a population flow network in the Yangtze River Delta in China. It explores the inter-city connections and spatial structures of regional urban networks as well as the correlations and differentiations of urban functions under multi-scale interaction. The results indicate that: (1) Regional network demonstrates notable multi-scale interactions with an explicit hierarchical structure; (2) The roles and positions of different cities vary significantly across scales due to economic, administrative, locational, and transportation differences; (3) Different city types can drive their evolution by navigating through rescaling in a diverse multi-scale environment; (4) A positive correlation is observed when comparing the functional behaviors of cities across various scales. This study provides insights for cities to identify their strategic roles and adapt development strategies within the wider network framework, offering theoretical and practical contributions to multi-scale urban networks analysis.

1. Introduction

The design of urban systems plays a crucial role in the strategic direction and urban development. Using deductive approaches, Christaller and Lösch made principal contributions to the central place model, which became the foundation for urban system research [1]. However, inter-city connections have surpassed the limitations of the central place theory. Various elements flow extensively at local, regional, national, and other scales, resulting in multi-scale urban networks. Urban networks are essential in understanding urban systems as the complexity of network configurations and spatial network positioning grant cities specific functions and positions [2].

Research on regional urban networks has attracted significant academic interest [3,4]. Many studies have centered on intra-regional connections and explored the network structures [5–7] and evolutionary trajectories [8,9] within a singular spatial dimension by employing complex network analysis. However, it is crucial to recognize that urban and regional developments are profoundly shaped by multi-scale factors. Kelly [10] argued that urban and regional development is shaped by factors both within and

* Corresponding author.
E-mail addresses: zsh1149@mail.dlut.edu.cn (S. Zhang), caimans@dlut.edu.cn (J. Cai), weiy742@nenu.edu.cn (Y. Wei), sxyangqiyao@dlut.edu.cn (Q. Yang), llm@mail.dlut.edu.cn (L. Li).

https://doi.org/10.1016/j.heliyon.2024.e30377
Received 23 January 2024; Received in revised form 22 April 2024; Accepted 24 April 2024
Available online 25 April 2024

outside the region. Gottmann [11] identified the megalopolitan belt as a connector, linking cities within the urban area to hubs (or gateways), notable for its multi-scalar connectivity. Scale is a critical factor when defining the functional role or positionality of a city. For instance, Knox and Taylor [12] highlighted the interdependence across scales as a primary feature of the world city concept and promoted recognizing "world city-ness" across different scales. Schmitt and Smas [13] pointed out that a city's status sensitively depends on the scales of the networks analyzed. Furthermore, focusing solely on one scale might overlook cities that serve specialized functions at specific spatial scales, such as gateway cities that connect city networks across multiple scales [14].

In essence, cities display complex scalar interactions, with growth influenced by hierarchical spatial scales amid diverse geographical landscapes. Current studies have not fully revealed the multi-scale dynamics and complexities of urban networks and overlooked the critical role of multi-scale interactions in shaping urban functions and their significance in a broader network framework. Some studies discussed the multi-scalar nature of urban networks and emphasized the interactions between global and local dynamics from an economic globalization perspective [15,16]. Nevertheless, this body of work primarily focuses on the "global" and "local" scales [17]. The ties between nation-states, regions, and other localities between the "global" and "local" realms, and their reciprocal impacts, remain under-studied.

As global value chains are morphing into national and regional chains. China proposed a strategy centered on domestic economic circulation. Restructuring across the nation-region-city scales is anticipated to be the core of China's regional governance in the coming era. Hence, research on the "nation-region-locality" scale is imperative for "urban positionality transformation" [2] and regional growth.

Castells [18] introduced the concept of the "space of flows", identifying its core elements as flows, networks, and network nodes. Within urban networks, cities and regions can function as network nodes. Human mobility, logistics, capital flows, and information circulations are as flow elements and connecting carriers. Inter-city connections, based on different "flows", offer unique viewpoints for examining urban networks. Scholars have increasingly examined these flows through various lenses, such as infrastructure pathways [19,20], organizational trajectories of enterprises pathways [21,22], and socio-cultural pathways [23,24], thus probing urban networks at multiple spatial scales. Population mobility plays a pivotal role in reshaping territorial dynamics [25]. Despite advancements in information technology, face-to-face communications remain essential. Motivated by business ties, travel, visits, or relocations, population mobility often reflects socio-economic values. Capitals, labor, and information flows alongside population movements across different territories, connecting cities to multi-scalar spatial landscapes and leveraging resources from multi-scalar networks. Therefore, population mobility is a crucial driving force in shaping multi-scale urban networks.

Considering the aforementioned, this study explores the characteristics of urban network and city functions within the Yangtze River Delta region in China from national, regional, and local scales. Analyzing the population mobility at different scales within the urban network. The research aims to provide a more detailed and comprehensive understanding of the mutual relationships between cities and the spatial organizational patterns of multi-scale networks. This, in turn, offers theoretical support and policy recommendations for cities to establish multi-scale division of labor and cooperation. The paper is organized as follows: Section 2 introduces the theoretical basis and gives the analytical framework. Materials and methods are described in Section 3, followed by analytical results in Section 4. Discussion and conclusion are drawn in section 5.

2. Theoretical basis

2.1. Networked scales

Scale is an essential tool in geography for analyzing spatial patterns, processes, and mechanisms of research elements [26]. The geographical scale has traditionally been construed as a relatively static hierarchy of bounded spaces with varying extents of power [27]. These relationships among scales are perceived as vertical and inherently nested, with smaller-scale units enveloped within more expansive ones. For instance, Taylor [28] advanced a global-nation-local scalar analytical framework, while Smith [29] proposed a scalar system ranging from individuals to the global level. Each scale represents a spatial "space of place" with clear boundaries and notable boundary effects. The rise of economic globalization and technological revolution resulting in "time-space compression", has fostered long-distance and transregional interactions among cities. Despite their spatial discontinuities, cities maintain intricate functional links, leading to misalignments between scale hierarchies and scopes [30]. Some scholars advocated for a horizontal network perspective of scales [31,32], where networks form horizontal spaces across geographically dispersed nodes. Cox [31] introduced a "networks of association" scalar framework and observed interactions without boundaries, suggesting permeable regional borders that enable elements separated by spatial constraints to converge.

Examining vertical scalar systems and horizontal relational networks separately offers insights into human geography. However, it limits the comprehensive understanding of diverse spatial processes. For instance, Nation-regional spatial arrangements combine elements of vertical and horizontal scalar constructions. Regional integration showcases relational horizontal scales while regional governance drives vertical-scale expansion. As a result, the joint development of scales and networks has garnered attention and debate. Brenner [33], for instance, emphasized the interdependence of geographical scales and relational networks. Bank and Van Heur [34] argued that networks are not purely egalitarian and flat but display a clear hierarchical structure. From another perspective, highlight networks' role play in connecting various scales, enabling "Jumping Scales" [31]. Leitner [35] posits that networks permeate and traverse scales, enabling different hierarchical scales to intertwine.

In conclusion, networks bridge scales, connecting actors within and across them. The scalar aspect of networks is not limited to horizontal orientations. It encompasses a geographical relational framework where layered hierarchies and networks coexist and intertwine.

2.2. Local buzz, global pipelines

Bathelt introduced the theoretical model titled "local buzz, global pipelines " [36]. "Local buzz" designates the informational and communicative environment formed when entities in close geographic proximity interact through face-to-face engagements. It emphasizes the frequent and sustained interactive collaboration at the local level and the agglomeration of economic activities. On the other hand, "global pipelines" pertains to channels of cooperation and information flow that cross extensive geographical spans, providing opportunities for local actors to access external knowledge and resources, thereby breaking the path dependence of the local system. The synergy between buzz and pipelines allows regions to access external resources and knowledge and circulate them locally, fostering economic advancement and bridging global-local interfaces.

The "local buzz, global pipelines" model emphasizes the role of spatial scale in local production systems. Within the "global-local" paradigm, "global" nor "local" exhibit considerable scalar fluidity rather than fixed scales. "Local" can encompass intra-city industrial sectors, industry conglomerates, urban centers, or even an entire geographical region. Non-local affiliations appear across varied spatial dimensions [37] and are not restricted to global connections. Domestic linkages, whether inter-city or inter-regional, can also be characterized as pipelines.

The "local buzz, global pipelines" model was initially applied to developing industrial clusters and has been extensively utilized in innovation networks. However, it is rarely used in other research areas. Based on leveraging cross-scale cooperation and communication, internal interactions, and external connections, the explanatory power of the "local buzz, global pipelines" model can be enhanced (refer to Fig. 1).

Anchored in the "buzz-pipelines" theoretical framework, this paper divides population mobility into two distinct modes: the intra-city "buzz" and the inter-city "pipelines". The "local buzz" encompasses information exchanges and knowledge intersections arising from urban population concentrations. A dense urban population suggests that cities harbor more significant potential for novel knowledge generation and economic value at the local level. The "pipelines" pertains to inter-city population flow encompassing regional and national levels. When cities forge numerous external connections, they inevitably tap into a wealth of pipelines to absorb external knowledge, information, and resources, thereby nurturing local knowledge innovation and economic expansion, and bolstering the city's standing within the network.

2.3. Framework of analysis

Based on the "networked scales" and the "local buzz, global pipelines" theoretical framework, this paper utilizes the population flow network as an empirical path to examine the multi-scale connections and cross-scale interactions of urban networks (see Fig. 2).

Multi-scale is one of the essential characteristics of urban networks. This study focuses on local, regional, and national scales. At the

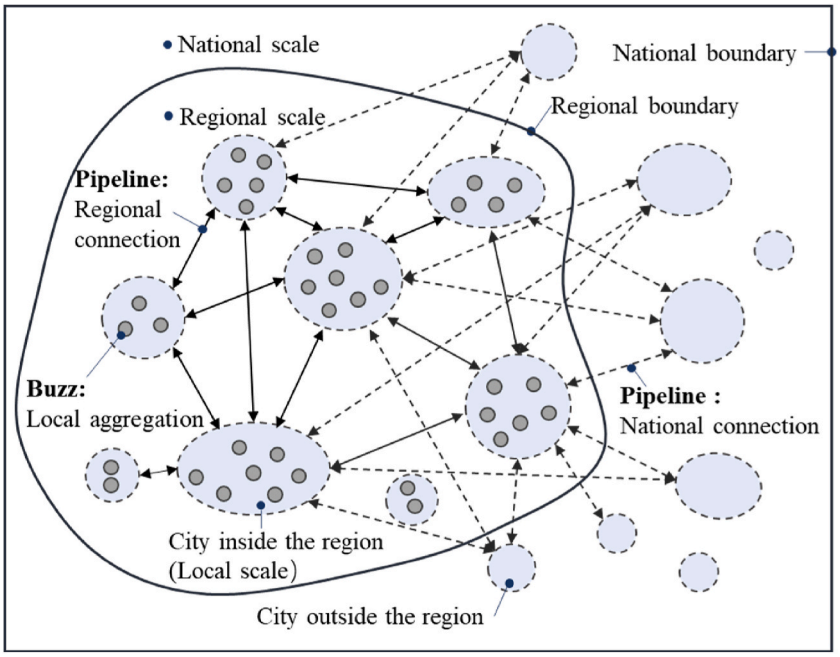


Fig. 1. Analytical model of muti-scale network based on "local buzz, global pipelines".
Conceptual diagram illustrating an analytical model for muti-scale network. The dynamics of urban development are divided into two distinct modes: the intra-city buzz and the inter-city pipelines. "Buzz" can be understood as local agglomeration, while "pipelines" pertains to inter-city connections, split into external contacts at both regional and national levels.

local scale, the city's functions demonstrate internal agglomeration and interactive capabilities. While their external regional and national connections reflect its functions at the regional and national scales, showcasing the city's radiating influence and competitive advantages across various scales.

Relationships within urban networks may exhibit distinct characteristics at different scales. By examining the connectivity and structural features of urban networks at various scales, we can study cities' scale bias—whether their external connections rely more on regional networks or tend to draw strength and resources from networks beyond the regional or larger scales. The concept of "polycentricity" is a pivotal lens for understanding the spatial structure of urban regions. The city-region may unveil a polycentric structure at a specific scale, while it may present as monocentricity at another scale. Analyzing polycentricity at diverse geographical scales allows for a comprehensive investigation of a city's position across various scales.

The functionality of a city across diverse spatial scales is interconnected rather than isolated. The accumulation of internal resources and interactions with external elements form a repetitive and accumulative cycle. As resources traverse networks of various scales, interactions occur between entities at these scales, leading to functional differentiation and correlation. The functional roles of cities should comprehensively reflect their abilities in aggregation, diffusion, circulation, and control of elements within nested multi-scale networks. Based on functional differentiation, cities are categorized as integrated cities, national-oriented cities, regional-oriented cities, local-oriented cities, and periphery cities. Simultaneously, this study attempts to elucidate the correlation effects between internal agglomeration (local functions) and external network connections (regional functions, national functions).

As recommendations and policy insights for urban development in multi-scale networks, cities can seek suitable positions and development scales within the urban network through rescaling. By guiding and optimizing network externality, cities can encourage more active interaction with external networks, enhancing their innovation and development levels.

3. Materials and methods

3.1. Study area

The Yangtze River Delta region, located on China's eastern coast within the lower stretches of the Yangtze River, is delineated by the river to its north and features the renowned Yangtze River Delta plain with its gently rolling terrain, contrasting with the hilly landscapes to its south. This region enjoys strategic transportation facilities, including state-of-the-art maritime ports and airports, and possesses a vast economic hinterland. It stands as a premier financial hub in China. Serving as the vanguard of China's reform and opening-up initiatives, the Yangtze River Delta has capitalized on its strategic location and robust industrial base, transforming into the most vibrant and open urban cluster in China's economic realm.

In response to "de-globalization", the Yangtze River Delta, historically a pivotal point of globalization and the international urban system, is shifting from relying on global value chains to a leadership role within the domestic value chain. Against this backdrop, a key challenge for cities within the Yangtze River Delta is determining their specific position and function in regional and national urban frameworks during the era of domestic circulation. Additionally, pinpointing the optimal scale strategy is an essential dilemma that requires immediate attention.

Since the 1990s, the territorial boundaries of the Yangtze River Delta have continually evolved. According to the " Outline of the Regional Integration Development Plan for the Yangtze River Delta." issued by China's central government in 2019, the Yangtze River

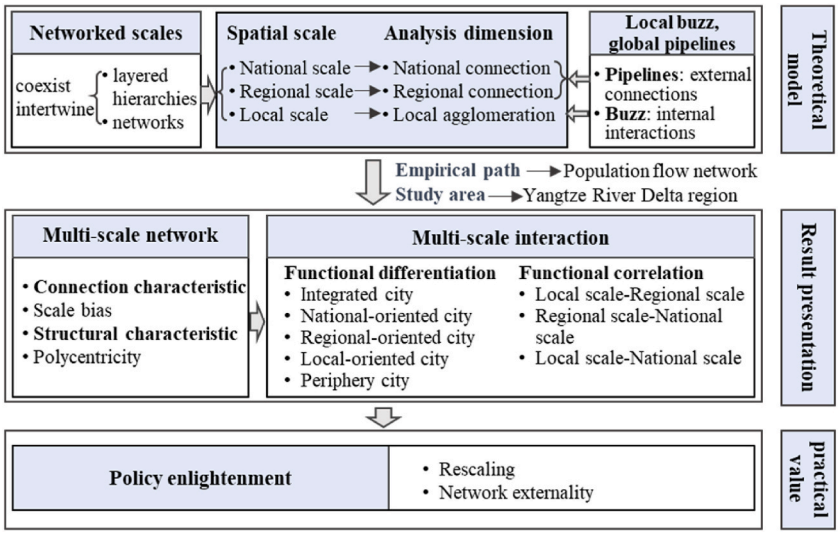


Fig. 2. Research approach and analytical framework.
Flowchart depicting a schematic overview of the analytical framework employed in the study, serving as a guide to the reader for understanding the research approach in the paper.

Delta region consists of 41 cities distributed across Shanghai, Jiangsu, Zhejiang, and Anhui provinces. These encompass the centrally administered city of Shanghai, three provincial capitals (Nanjing in Jiangsu, Hangzhou in Zhejiang, and Hefei in Anhui), and 37 prefecture-level cities (as shown in Fig. 3).

3.2. Research data

Recently, large-scale data with locational information has been extensively incorporated into urban network research [38,39]. Prominent Chinese internet giants, such as Baidu and Tencent, offer real-time dynamic data on population flow. This study employs Tencent's population migration data. Compared to Baidu's location data, Tencent's migration dataset has a time granularity of 24 h, which reduces the likelihood of long-distance routes being fragmented and encompasses nearly all long and short-distance flow trajectories. As one of China's most influential internet companies, Tencent offers digital products that span social networks, e-commerce, music, browsers, and more, effectively covering virtually all mobile smartphone users. Tencent utilizes the Location-Based Services (LBS) provided by its associated apps to gather geographic location requests from users' smart devices during specified intervals. A vast array of inter-city migration trajectories of individual users can be accessed through sophisticated processing of user location data while ensuring user privacy [39].

The Tencent migration data used in this study is derived from Tencent's Location Data Platform (https://heat.qq.com/qianxi.php). The platform provides a user interface and an application programming interface (API), allowing for collecting and utilizing population flow data via web scraping. This research harnesses Tencent's Location Data Platform to obtain daily population flow data from June 1 to June 30, 2019. The dataset chronicles the top ten inflow and outflow records for each city, with attributes including the origin city, destination city, inflow, outflow, and migration volumes via different transportation means such as highway, railway, and aviation (as shown in Table 1).

Data on the resident population is sourced from the annual statistical announcements released by Chinese city governments. This study employs the average resident population figures from the end of 2018 and 2019 for each city as the representative population during the research period.

3.3. Research methods

3.3.1. Network construction

For this study, cities and the mobility of residents between cities are positioned as nodes and the flow element of inter-city connections, respectively. The Yangtze River Delta region forms networks internally and concerning other Chinese areas. Urban network within the Yangtze River Delta region is recognized as the "regional network" rooted at the regional scale, while urban network

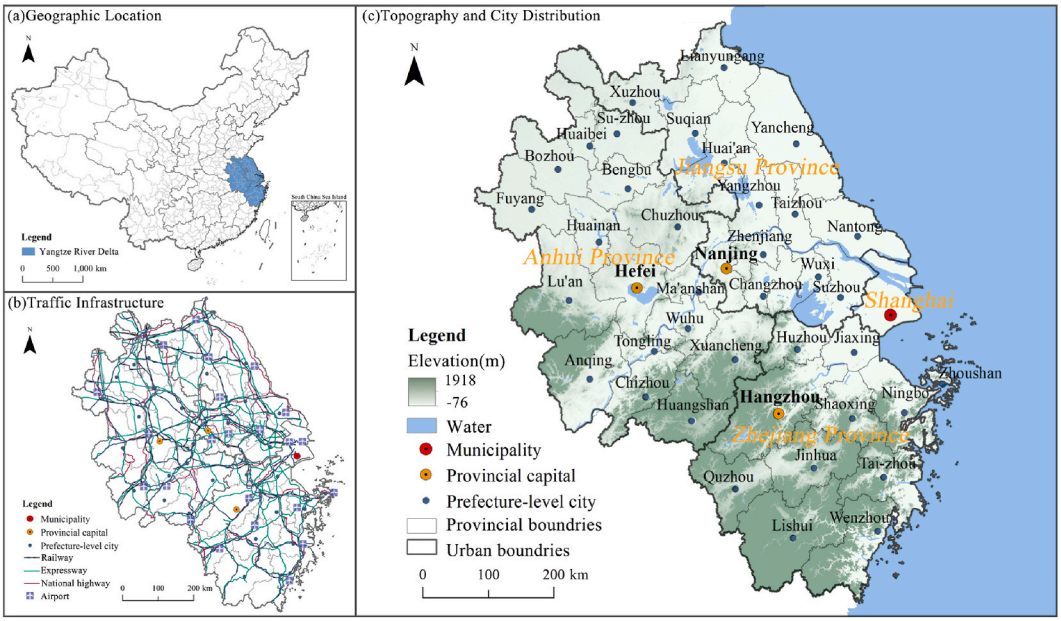


Fig. 3. The Yangtze River Delta region in China.
Composite figure providing a comprehensive visual representation of the geographic location, traffic infrastructure, and city distribution within the Yangtze River Delta. Subfigure (a) highlights the geographical location of the Yangtze River Delta in China, situated on the eastern coast within the lower reaches of the Yangtze River. Subfigure (b) provides a snapshot of the traffic situation in the YRD region, illustrating key transportation elements, including airports, railways, expressways, and national highways. Subfigure (c) depicts the spatial distribution of major cities within the Yangtze River Delta.

Table 1
Samples of raw data.

Date	Origin City	Destination City	Transportation	In/Out	Migration Volumes
2019-6-1	City1	City2	highway	outflow	75453
2019-6-1	City1	City3	railway	outflow	27313
2019-6-1	City1	City3	aviation	outflow	1758
…	…	…	…	…	…

between the Yangtze River Delta region and other areas in China corresponds to the "region-national network" situated at the national scale.

The population outflow from city i to city j is identical to the population inflow from city j to city i, which might potentially lead to redundant counting. To address this problem, a more accurate measure of the overall population flow between cities can be achieved by consolidating outflow and inflow routes and eliminating duplicate data. This culminates in creating a population flow matrix, represented as Equation (1):

$$S_{ij} = \begin{Bmatrix} 0 & S_{12} & \cdots & S_{1(n-1)} & S_{1n} \\ S_{21} & 0 & \cdots & S_{2(n-1)} & S_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ S_{(n-1)1} & S_{(n-1)2} & \cdots & 0 & S_{(n-1)n} \\ S_{n1} & S_{n2} & \cdots & S_{n(n-1)} & 0 \end{Bmatrix} \tag{1}$$

In the equation: n is the number of cities in the population flow matrix. S_{ij} represents the migration intensity from the origin city i to the destination city j, while S_{ji} represents the migration intensity from the origin city j to the destination city i ($i = 1,2,\cdots,n; j = 1,2,\cdots, n; i \neq j$). The weight of population flow between city i and city j is denoted as W_{ij}, which is calculated using Equation (2):

$$W_{ij=}S_{ij} + S_{ji} \tag{2}$$

This article will explore the external connections of cities in the Yangtze River Delta at both regional and national scales. Consequently, the data has been processed in two scenarios.

(1) Both the origin and destination are cities within the Yangtze River Delta. This yields a 41 × 41 O-D population flow matrix, which measures inter-city connections at the regional scale.
(2) Either the origin or destination is a city within the Yangtze River Delta, while the other is outside the Yangtze River Delta region. With 250 cities outside the Yangtze River Delta having connections with cities inside the Yangtze River Delta, this is represented by a 41 × 250 O-D matrix and is used to evaluate inter-city connections at the national scale.

3.3.2. Urban centrality

This study categorizes urban centrality into three distinct scales: local, regional, and national. Each of these scales signifies the city's importance at varying levels. The concept of local centrality, often termed "local buzz", encapsulates the city's capacity for internal agglomeration and interactions. The city's total resident population is the metric for this local scale. In contrast, centrality at the regional and national scales signifies the city's external connectivity, highlighting its ability to engage with other cities in resources, information, and other exchanges. Furthermore, it underscores the city's radiating influence and competitive edge at these scales. We selected the city's total external connections as the metric for this type of centrality, as it vividly portrays the city's interconnectivity within a broader urban network. Specifically, regional centrality pertains to a city's connections with other cities within its region, while national centrality accounts for connections with cities beyond its region.

To assess the degree of polycentricity across different spatial scales, this study employs the Gini coefficient, a recognized metric for measuring inequality. The methodological details for this calculation are available in the cited literature [40]. The Gini coefficient ranges from [0,1], with a lower value suggesting a more pronounced polycentric trait within the given region.

3.3.3. Urban functional role delineation based on multi-scale network

Urban network centrality is often used to determine cities' roles or positions within urban networks [41–43]. Some studies have examined the functions of urban network from various perspectives. For example, according to the two-dimensional characteristics of centrality and power, Neal classifies world cities into quintessential, hub, and gateway world cities [41]. Liu et al. identify four city types by analyzing inter-city and intra-city polycentricity: cities with high levels of both, cities with low levels of both, and cities with contrasting levels of polycentricity [44]. Wei et al. distinguish cities as inter-oriented or extra-oriented based on their internal and external information connections [2].

This study expands on prior research by analyzing population mobility network to uncover cities' functional differences across local, regional, and national scales. Depending on a city's centrality at varying scales and using mean values as a benchmark, cities in the Yangtze River Delta region can be classified into five categories: integrated cities, national-oriented cities, regional-oriented cities, local-oriented cities and periphery cities (as shown in Table 2).

(1) Integrated cities: These cities manifest high centrality across several scales. They have both a remarkable capacity for resource aggregation and pronounced external connectivity, thereby acting as pivotal nodes for population mobility at all scales.
(2) National-oriented cities: These cities have a strong presence in the national-scale urban network but exhibit limited interactions with other cities in the region. Their primary function is to serve as conduits facilitating the region's integration into the larger national urban framework.
(3) Regional-oriented cities: Notably central at a regional scale, these cities establish close economic relationships and interactions with other cities nearby. However, their position in the national functional hierarchy is somewhat diminished.
(4) Local-oriented cities: Despite their significant size, these cities are largely dependent on their internal systems for expansion. Their urban networks are somewhat insular, leading to a lower degree of nodality in the broader urban matrix.
(5) Periphery cities: These cities have tenuous connections both at a local level and external level.

3.3.4. Correlation index between multi-scale urban function

To analyze the interplay of cities' functions at different spatial scale, this study uses correlation coefficients between centralities at these scales to measure the interconnected effects of urban functions. The computational formula is presented as Equation (3):

$$R_{X-Y}=\frac{\sum (x-\bar{x})(y-\bar{y})}{\sqrt{\sum (x-\bar{x})^2 \sum (y-\bar{y})^2}} \tag{3}$$

In the equation: R_{X-Y} represents the correlation between urban functions across scales X and Y. Here, x denotes epitomizes the city's centrality at scale X, while y represents the same at scale Y. Meanwhile, $\bar{x}$ and $\bar{y}$ indicate the average centrality values for cities at the specified designated scales X and Y, respectively.

4. Results

4.1. Multi-scale urban networks of population flow

4.1.1. Inter-city connections at different scales

Using ArcGIS, the population flow network within the Yangtze River Delta (as shown in Fig. 4) and the Yangtze River Delta-other areas in China population flow network (as shown in Fig. 5) are visualized. Inter-city population mobility intensity is categorized into five levels using natural breaks classification. Overall, the urban network in the Yangtze River Delta exhibits a multi-scaled spatial characteristic.

From a regional standpoint, inter-city connections in close proximity are emblematic of the prevailing trends of population flow within the Yangtze River Delta. The significance of geographical proximity is evident: cities within a straight-line distance of 120 km represent 8.5 % of all connectivity edges. However, these connections account for 41.3 % of the overall flow. High-tier connections typically form between central cities and their adjacent counterparts. This is evident in city pairs such as Shanghai-Suzhou, Suzhou-Wuxi, Hangzhou-Jiaxing, Hangzhou-Shaoxing, Hangzhou-Shanghai, Changzhou-Wuxi, Hefei-Lu'an, Nanjing-Zhenjiang, and Shanghai-Jiaxing, which demonstrate the highest frequency of population flow. The prominence of the corridor effect in urban regional linkages is apparent; cities situated along major transport routes often form strong connections with their neighbors. In the eastern portion of the region, the primary connections form a "Z"-shaped backbone, extending from Southern Jiangsu through Shanghai to Northern Zhejiang. Conversely, in the western part, the focus is on Hefei, the capital of Anhui province. Due to geographical impediments, such as challenging terrains and less developed transportation infrastructure, the southern region of Anhui province and the southwestern part of Zhejiang province generally exhibit weaker connection strengths, resulting in limited inter-city exchanges.

From a national standpoint, the Yangtze River Delta's external connections exhibit a dual characteristic of proximity and orientation towards developed regions. Cities that maintain strong external ties are primarily located at the regional boundary and in prominent urban agglomerations such as the Jing-Jin-Ji, Pearl River Delta, and Chengdu-Chongqing clusters. In the region's northern section, cities such as Xuzhou, Fuyang, and Lianyungang have forged strong associations with external cities like Linyi, Jining, and Zhoukou, predominantly through highways. In contrast, national or broader regional connections appear less constrained by geographical space. Centralized connections link cities that stand at the pinnacle of economic development in the country. Originating from core cities within the Yangtze River Delta, like Shanghai, Hangzhou, and Nanjing, these linkages extend to other national central cities, including Beijing, Chengdu, Guangzhou, Shenzhen, and Wuhan.

Table 2
Classification of urban roles based on multi-scale network.

Role of Cities	Local Centrality	Regional Centrality	National Centrality
Integrated City	High	High	High
National-oriented City	High or Low	Low	High
Regional-oriented City	High or Low	High	Low
Local-oriented City	High	Low	Low
Periphery City	Low	Low	Low

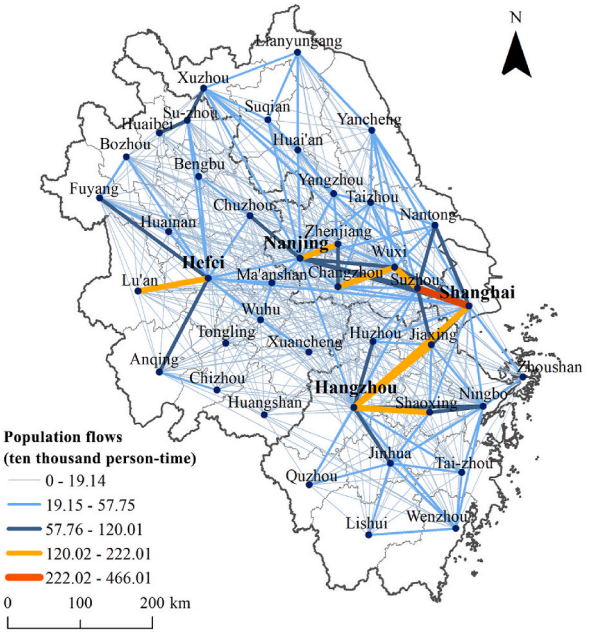


Fig. 4. Urban network based on population flow within the Yangtze River Delta region.
Network visually representing the population flow network within the Yangtze River Delta. Inter-city population mobility intensity was categorized into five distinct levels using the natural breaks classification. The color gradient signifies varying degrees of connectivity intensity. The close proximity of inter-city connections on the map reflects the prevailing trends of population flow within the Yangtze River Delta. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

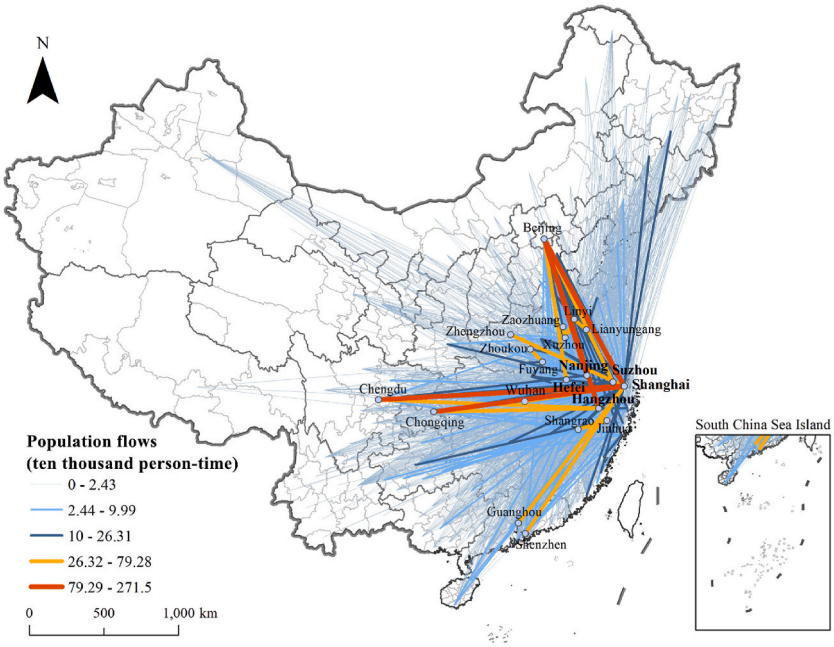


Fig. 5. Urban network based on population flow between the Yangtze River Delta region and other areas in China.
Network visually representing the population flow network between Yangtze River Delta region and other areas in China. Inter-city population mobility intensity was categorized into five distinct levels using the natural breaks classification. The color gradient signifies varying degrees of connectivity intensity. The map reveals a dual characteristic of these external connections, emphasizing both geographical proximity and an orientation toward developed regions. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4.1.2. Scale bias in inter-city connections

In their external engagements, cities often integrate into networks of varying scales. This study examines the distribution of external connections across these scales to understand the bias in scale of cities in city network (as shown in Fig. 6). A higher percentage of connections beyond the region indicates cities' greater inclination to acquire development resources from the national-scale urban network. In general, economically developed cities and those on the region's periphery prefer connecting with national networks. In contrast, smaller cities and those in the central region are more inclined to establish regional connections.

Central cities in the Yangtze River Delta, including Shanghai, Nanjing, and Hangzhou, maintain a higher proportion of national-scale connections in their external engagements. Unlike other central cities, Suzhou leans more towards regional links. Its proximity to Shanghai allows it to benefit from the ripple effects of Shanghai's economic strength. Additionally, its neighboring cities, like Wuxi and Changzhou, are economically robust, nudging Suzhou towards greater dependence on the regional urban network for its growth. As provincial capitals, Hangzhou and Nanjing possess substantial administrative and economic influence, enabling them to spearhead and manage broad inter-city partnerships, and consolidate their central roles in expansive urban networks.

Cities with significant external connections, such as Xuzhou, Lianyungang, Fuyang, Wenzhou, Quzhou, and Jinhua, are chiefly located on the region's outskirts. While these peripheral cities have limited direct ties to central cities, resulting in increased associated costs and a lesser integration into the core regional network. Their strategic external connectivity aids in their assimilation into the national network. For example, Lianyungang is the terminal of the vital Lanzhou-Lianyungang railway line, marking its significance as a transport nexus. Tai-zhou is a critical conduit linking China's coastal region to its southwestern territories. These cities also boast airports, boosting their external links. This vast network provides access to essential resources and data, propelling their urban development at a national level.

Cities with a dominant share of regional connections are primarily found in the central regions of Anhui and Jiangsu provinces. Among them, Xuancheng, Huai'an, Taizhou, Yancheng, and Huainan have the highest regional link proportions. These cities rank lower in economic development within the Yangtze River Delta. Their limited economic growth and smaller industrial bases make it difficult to forge links with national cities. As a result, their access to the resources vital for urban growth primarily hinges on the regional urban network.

4.2. Regional polycentricity at different scales

4.2.1. Urban centrality spatial structure

Using the natural break classification, the centrality of cities in the Yangtze River Delta at different scales is categorized into four distinct tiers. This categorization is depicted in Fig. 7, which outlines the hierarchical structure of city centrality at various scales. The

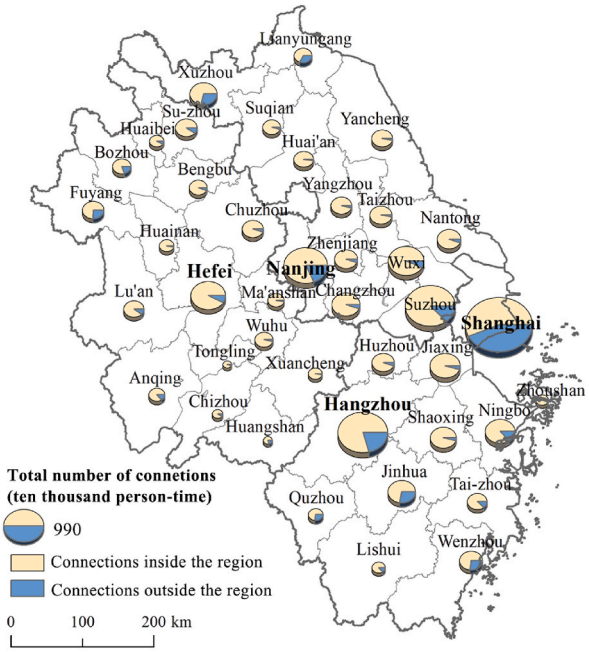


Fig. 6. The proportion of inter-city connections at different scales.
Pie chart overlaid on a geographical map displaying the distribution of inter-city connections at different scales to understand the preference in scale of connections of cities in the Yangtze River Delta. The yellow segment represents regional-scale connections, while the blue segment signifies national-scale connections. A higher percentage of blue indicates a greater inclination of cities to acquire development resources from the national-scale urban network. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

diagram indicates that the spatial structure of the Yangtze River Delta has significant scale-dependent variations. As the scale increases, both the tiers and the spatial distribution of city centrality undergo noticeable changes.

From local scale, the Yangtze River Delta displays a spatial pattern typified by "one dominant, multiple strong". Shanghai emerges as the primary first-tier city, acting as a significant attraction for population and resources. The second tier, encompassing cities such as Nanjing, Xuzhou, Fuyang, and Hangzhou, has a more distributed spatial arrangement.

On the regional scale, the Yangtze River Delta transforms into a polycentric spatial configuration with central cities including Shanghai, Suzhou, Hangzhou, and Nanjing. Cities of high centrality are closely grouped, with the aforementioned central cities providing a guiding influence over surrounding areas. Owing to their formidable economic strength, Shanghai, Suzhou, Nanjing, and Hangzhou act as pivotal nodes, drawing population flows within the region and occupying the top tier. Cities like Wuxi, Hefei, Jiaxing, Ningbo, and Changzhou comprise the second tier. Their strategic locations, close to the central cities, allow them to leverage the beneficial effects of these primary hubs, subsequently boosting their population attraction potential. The third-tier cities are predominantly located in the east-central part of the Delta, whereas fourth-tier cities are mostly found in the region's western and southern peripheries.

On national scale, the structure leans towards a mono-centric configuration with Shanghai at its focal point. Shanghai is the only first-tier city, primarily tasked with driving business transactions and facilitating flows between the Yangtze River Delta and other major national cities. Hangzhou, Nanjing, and Suzhou are positioned in the second tier. Cities located the region's northern boundary, including Xuzhou, Fuyang, and Lianyungang, as well as Zhejiang's Ningbo, Jinhua, and Wenzhou, are categorized in the third tier. Areas with limited inter-city population flows at this scale are extensively distributed within the inner region of the Delta.

4.2.2. Polycentricity of Yangtze River Delta

Table 3 presents the centrality rankings of the top ten cities across various scales, their centrality ratios relative to the top-ranked city, and the polycentricity index at different scales. From this table, it is clear that the polycentricity for the Yangtze River Delta decreases as the spatial scale increases. This finding suggests that polycentricity is scale-dependent: as the spatial scale enlarges, the distinction in the polycentric structure lessens. Shanghai boasts a pronounced primacy on the local scale. However, it does not maintain an unchallenged supremacy within the Yangtze River Delta on the regional scale while its dominance markedly surpasses that of other cities on the national scale, with the polycentricity reaching its nadir. This observation implies that cities' external connections manifest a threshold effect: high-order cities are more adept at consolidating resources and elements within the network. As the spatial scale expands, the variance in city centrality grows more evident, intensifying the disparity in urban rankings.

4.3. Muti-scale interaction: functional differentiation and functional correlation

4.3.1. Functional differentiation characteristic

Using the classification method detailed in Section 3.3.3, cities within the Yangtze River Delta have been categorized into five types. Fig. 8 presents a three-dimensional scatter plot depicting city centrality across national, regional, and local scales. This visual representation clearly displays the relative positions of cities at each scale (as shown in Fig. 8(a and b)).

Shanghai, Hangzhou, Nanjing, and Suzhou emerge as the integrated cities of the Yangtze River Delta, serving as the principal hubs and organizational pivots within the population flow network of the region. These cities fulfill intermediary and bridge roles within multi-scale network. They benefit not only from dense local interactions but also from the influx of new resources from higher-scaled mobilities. Hefei, Ningbo, Wuxi, Changzhou, Jiaxing, and Shaoxing, identified as regional-oriented cities, are strategically positioned

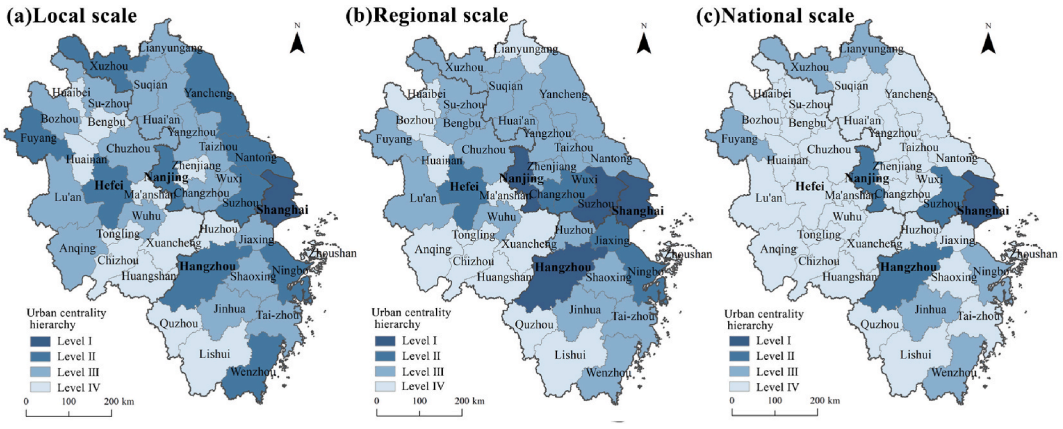


Fig. 7. Hierarchical structure of urban centrality in the Yangtze River Delta at different scales.
Composite figure illustrating the spatial structure of city centrality at local, regional, and national scales. Using the natural break classification, the centrality of cities at different scales is categorized into four distinct tiers, with darker colors indicating higher centrality rankings. The figure indicates t the scale dependency in the spatial structure of the Yangtze River Delta region, emphasizing the variations in centrality across different geographic scales. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Urban centrality and regional polycentricity index at different scales.

	Local Scale		Regional Scale		National Scale	
1	Shanghai	1	Shanghai	1	Shanghai	1
2	Suzhou	0.443	Suzhou	0.873	Hangzhou	0.255
3	Hangzhou	0.416	Hangzhou	0.781	Nanjing	0.176
4	Wenzhou	0.382	Nanjing	0.623	Suzhou	0.158
5	Xuzhou	0.363	Wuxi	0.472	Xuzhou	0.107
6	Nanjing	0.349	Hefei	0.442	Jinhua	0.071
7	Ningbo	0.345	Jiaxing	0.346	Wenzhou	0.061
8	Fuyang	0.339	Ningbo	0.300	Fuyang	0.058
9	Hefei	0.335	Changzhou	0.299	Ningbo	0.052
10	Nantong	0.301	Shaoxing	0.252	Lianyungang	0.044
Polycentricity index	0.325		0.457		0.741	

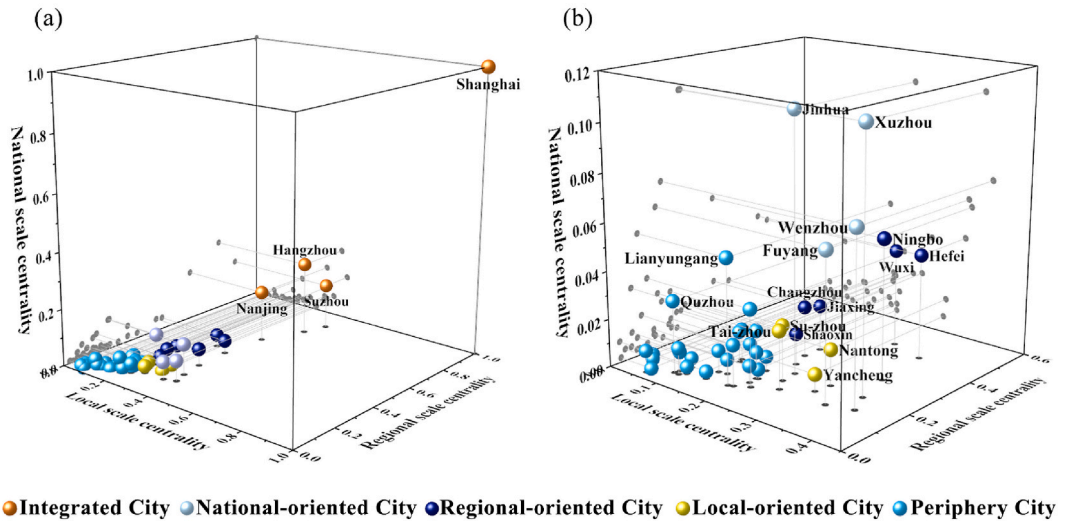


Fig. 8. Three-dimensional scatterplots of urban centrality.
Three-dimensional scatter plot showcasing city centrality at national, regional, and local scales. (b) is a detail view of (a). Cities in the Yangtze River Delta are categorized into five types: core cities, national gateway cities, regional hub cities, local node Cities, and periphery cities. The plot visually displays the distinct roles and positions of cities within the multi-scale network.

in the Yangtze River Delta's heart, enabling widespread connections with other cities in the area. Conversely, the Yangtze River Delta's national-oriented cities, including Xuzhou, Jinhua, Wenzhou, and Fuyang, are mainly located on the region's outskirts. Cities such as Su-zhou, Nantong, Tai-zhou and Yancheng are local-oriented cities. Positioned centrally in the region and at a distance from major transport arteries, their urban development leans heavily on local resource advantages and internal aggregation, with weaker external connections. Some medium and smaller cities, constrained by their economic development levels, find it challenging to access core

Table 4
Classification of urban functional roles.

Functional Role of Cities	Role in Multi-scale Network	Role in Plannings	City
Integrated Core	Integrated	Core	Shanghai
Integrated Hubs		sub-core	Hangzhou、Nanjing、Suzhou
Regional-oriented Hubs	Regional-oriented		Hefei、Wuxi、Ningbo、Changzhou、
Regional-oriented Nodes		general	Jiaxing、Shaoxing
National-oriented Nodes	National-oriented		Xuzhou、Jinhua、Wenzhou、Fuyang
Local-oriented Nodes	Local-oriented		Su-zhou、Nantong、Yancheng、Tai-zhou
Periphery Cities	Periphery		Lianyungang、Haozhou、Quzhou、Lu'an、Anqing、Huzhou、Zhenjiang、Chuzhou、Lishui、Bengbu、Huangshan、Yangzhou、Huaibei、Suqian、Wuhu、Taizhou、Zhoushan、Chizhou、Ma'anshan、Huai'an、Huainan、Xuancheng、Tongling

resources within the urban network, positioning them as peripheral cities in the Yangtze River Delta's urban matrix.

The functions and positions of cities are essential in formulating development objectives and strategies. This paper aligns urban roles outlined in planning documents with cities' roles in the multi-scale network, enhancing research precision. It amalgamates the city system proposed in existing regional plans, such as the "Yangtze River Delta Regional Plan (2009–2020)," the "Yangtze River Delta Urban Agglomeration Development Plan (2016–2030)," and the "Outline of the Regional Integration Development Plan for the Yangtze River Delta (2019)." Cities are classified into three levels: Shanghai emerges as the exclusive core city; Changzhou, Wuxi, Suzhou, Nantong, Ningbo, Hefei, and Hangzhou are designated as sub-core cities; and the rest are identified as general cities.

Table 4 details the results of the city functional roles classification. This classification underscores the strategic integration of city positioning within broader urban networks and planning paradigms, further categorizing cities into integrated core, integrated hubs, regional-oriented hubs, national-oriented nodes, local-oriented nodes, and periphery Cities.

Shanghai, as the Yangtze River Delta's singular core city. It possesses formidable comprehensive strengths, markedly surpassing other cities in political, economic, and cultural dimensions. Hangzhou, Nanjing, and Suzhou are integrated hubs in the Yangtze River Delta. Hefei, Wuxi, Ningbo, and Changzhou show a discernible gap compared to the other sub-core cities, lacking adequate national-level connectivity and thus positioned as regional-oriented hubs. Jiaxing and Shaoxing are geographically proximate to Shanghai and Hangzhou, elevating their network status by cultivating close ties with these integrated counterparts, classified as regional-oriented nodes.

Xuzhou, Jinhua, Wenzhou, and Fuyang are identified as national-oriented nodes. pivotal within the broader framework. Though these cities are designated as general within regional plannings, their proactive involvement in the national population network underscores their critical roles as key nodes in the nationwide network. Xuzhou and Fuyang, located on the northern periphery of the region, have limited connections to the eastern central cities of the Yangtze River Delta. They focus on integrating into other regions by fostering cross-regional collaborations with external neighboring cities, as shown in Fig. 5. For example, Fuyang has forged strong ties with nearby Zhumadian and Zhoukou through major road networks. Meanwhile, Xuzhou, together with cities like Suqian, Lianyungang, Suzhou (in Anhui province), Huaibei, and cities in Henan like Shangqiu and in Shandong like Jining and Zaozhuang, jointly establishes the Huaihai Economic Core Zone. The National Development Commission of China released the "Development Plan for the Huai River Ecological Economic Zone" in 2018, elevating it to a national strategic level. The Huaihai Economic Zone exemplifies cities seeking external development through cross-regional collaboration. Jinhua and Wenzhou, on the other hand, have extended their reach beyond regional boundaries to the national level by transforming their local production modalities and industrial systems. Wenzhou introduced the "Wenzhou Model" of private enterprise-led development, fostering a division of labor system reflecting modern market economics. Jinhua's commodity market is prosperous, Yiwu, China's largest small commodity trading base, is located in Jinhua, facilitating the distribution of goods nationwide and worldwide. These national-oriented nodes in the Yangtze River Delta all oriented breakthroughs by elevating their scale and looking beyond the region.

4.3.2. *Functional correlation characteristic*

According to Formula (3), the cross-scale functional correlation indexes for the Yangtze River Delta region, different provinces, and various types of cities are determined. The results are presented in Table 5. When observed broadly, the functional correlation indices at different scales within the Yangtze River Delta region are prominently significant, all registering values above 0.7. These indices point to a positive correlation effect across various scales.

High correlation indices are observed between local scale urban centrality (LC) and regional scale urban centrality (RC), as well as national scale urban centrality (NC), are high. This emphasizes that interactions within cities, which lead to agglomeration economies, enhance a city's external connections. In tandem, heightened external connectivity can amplify a city's internal agglomeration economy. A notably stronger correlation between LC and NC suggests that internal agglomeration significantly elevates a city's standing within the national functional network. Conversely, regional scale connections are markedly affected by factors such as distance friction and geographical positioning. Hence, the influence of internal agglomeration on a city's functional status at the regional scale is more subdued than at the national scale. Positive synergies are also evident between regional and national scale inter-city connections (RC and NC). The urban network in the Yangtze River Delta acts as a "conduit" for population and resource flows, both intra-regionally and beyond. Cities serving as transit hubs, strategically situated at these "conduit" intersections, forge functional connections with cities within and outside the region, thereby promoting a synergistic evolution of regional and national functions.

When the four central cities—Shanghai, Hangzhou, Nanjing, and Suzhou—are excluded, the cross-scale correlation indices for medium and smaller cities in the Yangtze River Delta region decrease significantly. This infers that cross-scale interactions are more pronounced in the region's central cities. From a provincial vantage point, Zhejiang province demonstrates the most robust correlation between RC and NC, signifying a pronounced mutual enhancement between regional and national connections. Cities in Zhejiang,

Table 5
Correlation index between multi-scale function.

Relevant Scales	Yangtze River Region	Zhejiang Province	Jiangsu Province	Anhui Province	Small and Medium Cities	Central Cities
R_{LC-RC}	0.813**	0.684*	0.732**	0.752**	0.601**	0.838
R_{LC-NC}	0.878**	0.710*	0.784**	0.908**	0.655**	0.987*
R_{RC-NC}	0.741**	0.846**	0.795**	0.579*	0.339*	0.754

Note : * indicates significant at the 5 % level and ** indicates significant at the 1 % level.
LC: Local scale centrality RC: Regional scale centrality NC: National scale centrality.

bolstered by efficient external transportation networks, can adeptly cultivate internal and external connections. Jiangsu province showcases a fairly uniform cross-scale functional correlation across its indices. Conversely, cities in Anhui province display the strongest correlations between LC and RC, as well as LC and NC, denoting a tightly interwoven bond between their agglomeration capacities and external functions.

5. Discussion and conclusion

5.1. Discussion

Urban development is influenced by forces at multiple scales. A multi-scale perspective enables a comprehensive understanding of urban relationships and functional roles. “Local buzz, global pipelines” model establishes a foundational framework for multi-scale urban networks research based on leveraging cross-scale cooperation and communication, internal interactions, and external connections.

Within an open urban network system, cities cannot rely solely on resources at a single scale for development and accumulation. Cities can either forge or join different scale city networks based on their developmental imperatives. This leads to an upward or downward reallocation and connections, thereby introducing a "rescaling" developmental paradigm. Lower-tier cities can circumvent their entrenched hierarchical constraints and the limitations of traditional geographic proximity by forging higher scalar external connections, thus directly competing for resources, privileges, and networked statuses typically reserved for higher scalar echelons. For example, Cities like Xuzhou and Wenzhou, classified as national-oriented nodes, elevate their scale within urban networks by engaging in cross-regional collaborations and transitioning production models, thereby accessing resources for national-scale development. Meanwhile, regional-oriented nodes like Jiaxing and Shaoxing, leverage their geographic proximity to central cities, establishing tight collaborations with neighboring central cities. Through mechanisms like borrowed size and network externalities, these cities share the broader benefits generated by larger central cities.

Positive correlation is observed when comparing the functional behaviors of cities across various scales. This suggests that local governments should simultaneously focus on internal interactions and external connections within cities when formulating development strategies. Intervening and promoting urban rescaling through network links and factor supply-demand, is crucial in this context. Strengthening transportation infrastructure, especially those less influenced by distance decay effects like high-speed railways and aviation, can help cities establish connections beyond regional boundaries and tap into broader network externalities. Meanwhile, enhancing the "local space" to improve the capacity to adhere and attach to external resources is vital for facilitating the breakthroughs of development pathways.

Connections between cities are tighter at lower hierarchical scales, and sparser at higher ones. The Yangtze River Delta’s urban network, centered around cities like Shanghai, Suzhou, Hangzhou, and Nanjing, shows a polycentric structure with close connections among these central cities and their neighbors. Notably, key regions such as the Shanghai metropolitan area, the Suzhou-Wuxi-Changzhou metropolitan area, and the Nanjing metropolitan area, owing to their high levels of urban cohesion, serve as crucial supports for the regional urban network. This structure aligns with current goals to crucial urban integration within metropolitan areas. Looking ahead, the Yangtze River Delta could foster a relatively balanced polycentric network by improving resource flow within and among metropolitan areas. However, at the national scale, the Yangtze River Delta displays a unimodal pattern dominated by Shanghai, with external connections primarily sustained through the region’s integrated cities. To support the "domestic economic circulation " strategy, overcoming the administrative barriers that restrict the flow of external resources and encouraging cross-regional cooperation are essential. By leveraging Shanghai, Nanjing, Hangzhou, and national-oriented cities as gateways and bridges in the multi-scale urban network, other cities within the region can be integrated into a broader urban network, thus promoting the efficient allocation of resources and the development of regional integration. This approach not only enhances the organizational efficiency of spatial resources but also propels the region’s integration into the national network.

5.2. Conclusion

This study extends and elaborates on the "local buzz, global pipelines" model, constructing a multi-scale analysis framework of regional urban networks encompassing national, regional, and local dimensions. From a multi-scale perspective, it examines regional urban networks’ connectivity characteristics, spatial structures, and cities’ functional correlations and differentiations.

The main empirical findings from the Yangtze River Delta region are as follows: (1) Scale dependency of urban networks: Multi-scale analysis reveals distinct connectivity and structural characteristics of urban network at the national, regional, and local scales. (2) Scale bias in muti-stale networks: economic performance, administrative hierarchy, geographic positioning, and transportation influence a city’s scale orientation. A higher administrative ranking, adjacency to other regions, and efficient external transportation facilitate a city’s integration into national networks. (3) Rescaling for transformational development: Different city types can drive their evolution by navigating through rescaling in a diverse multi-scale environment. (4) Positive correlation among city functions across scales: The mobility of populations within urban networks connects scales, generating interactive effects.

Current scholarly discussions lack adequate empirical research on regional urban networks from a multi-scale perspective. This paper introduces an innovative multi-scale analytical framework that extends beyond the confines of single-scale analyses, incorporating interactions across local to national levels. Moreover, by classifying cities based on their multi-scale positions, our research reveals a new method for interpreting and defining urban functional roles. This offers theoretical support and policy recommendations for cities to identify strategic roles and establish collaborative divisions of labor. Empirical findings highlight multi-scale networking

behaviors' implications for urban strategy and policy, showcasing the practical value of multi-scale framework.

While this research analyzes the multi-scale characteristics of urban networks for a single year, it does not track the dynamic changes within the network. Nevertheless, scales constantly adjust, impacting power and control levels, which may restructure spatial organization and governance. Analyzing only one year lacks depth in tracing shifts in urban control across multiple scales. Future investigations could utilize data from multiple years to delve into the evolution of cities' roles within multi-scale urban networks. This approach will further enhance our understanding of scale interaction effects, complementary effects, and rescaling's role in urban and regional development. In addition, this study opted for human mobility as a representative measure to examine the characteristics of multi-scale urban networks. However, urban connectivity involves various spatial interactions like the flow of goods, capital, information, and technology. Cities may occupy different positions and serve various functional roles in different networks. Relying solely on human mobility may introduce bias. Future research could use a more diverse set of flow data, considering multiple factors to interpret multi-scale urban networks comprehensively.

Data availability statement

Data will be made available on request.

Funding

This research did not receive any specific funding.

CRediT authorship contribution statement

Shaohua Zhang: Writing – original draft, Methodology, Formal analysis. **Jun Cai:** Writing – review & editing. **Ye Wei:** Data curation, Conceptualization. **Qiyao Yang:** Writing – review & editing. **Lemei Li:** Visualization, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The author thanks all the research workmates for their helpful suggestions and patient guidance.

References

[1] G.F. Mulligan, M.D. Partridge, J.I. Carruthers, Central place theory and its reemergence in regional science, Ann. Reg. Sci. 48 (2012) 405–431, https://doi.org/10.1007/s00168-011-0496-7.
[2] Y. Wei, J. Wang, S. Zhang, et al., Urban positionality in the regional urban network: through the lens of alter-based centrality and national-local perspectives, Habitat Int. 126 (2022) 102617, https://doi.org/10.1016/j.habitatint.2022.102617.
[3] E. Meijers, Polycentric urban regions and the quest for synergy: is a network of cities more than the sum of the parts? Urban Stud. 42 (4) (2005) 765–781, https://doi.org/10.1080/00420980500060384.
[4] M.J. Burger, B. van der Knaap, R.S. Wall, Polycentricity and the multiplexity of urban networks, Eur. Plann. Stud. 22 (4) (2014) 816–840, https://doi.org/10.1080/09654313.2013.771619.
[5] J. Marull, C. Font, R. Boix, Modelling urban networks at mega-regional scale: are increasingly complex urban systems sustainable? Land Use Pol. 43 (2015) 15–27, https://doi.org/10.1016/j.landusepol.2014.10.014.
[6] Q. Lin, M. Xiang, L. Zhang, et al., Research on urban spatial connection and network structure of urban agglomeration in Yangtze River Delta—based on the perspective of information flow, Int. J. Environ. Res. Publ. Health 18 (19) (2021) 10288, https://doi.org/10.3390/ijerph181910288.
[7] D. He, Z. Chen, T. Pei, et al., Analysis of structural evolution and its influencing factors of the high-speed railway network in China's three urban agglomerations, Cities 132 (2023) 104063, https://doi.org/10.1016/j.cities.2022.104063.
[8] B. De Goei, M.J. Burger, F.G. Van Oort, et al., Functional polycentrism and urban network development in the Greater South East, United Kingdom: evidence from commuting patterns, 1981–2001, Reg. Stud. 44 (9) (2010) 1149–1170, https://doi.org/10.1080/00343400903365102.
[9] F. Zhang, Y. Ning, X. Lou, The evolutionary mechanism of China's urban network from 1997 to 2015: an analysis of air passenger flows, Cities 109 (2021) 103005, https://doi.org/10.1016/j.cities.2020.103005.
[10] P.F. Kelly, From global production networks to global reproduction networks: households, migration, and regional development in Cavite, the Philippines, Reg. Stud. 43 (3) (2009) 449–461, https://doi.org/10.1080/00343400902777075.
[11] J. Gottmann, Megalopolis or the urbanization of the northeastern seaboard, Econ. Geogr. 33 (3) (1957) 189–200. https://www.tandfonline.com/doi/abs/10.2307/142307.
[12] L.P. Knox, P.J. Taylor (Eds.), World Cities in A World-System, Cambridge University Press, Cambridge, UK, 1995, https://doi.org/10.1017/cbo9780511522192.002.
[13] P. Schmitt, L. Smas, Nordic "Intercity Connectivities" in a Multi-Scalar Perspective, Nordregio, Stockholm, 2012. https://urn.kb.se/resolve?urn=urn:nbn:se:norden:org:diva-117.
[14] Y. Li, N. Phelps, Megalopolis unbound: knowledge collaboration and functional polycentricity within and beyond the Yangtze River Delta region in China, 2014, Urban Stud. 55 (2) (2018) 443–460, https://doi.org/10.1177/0042098016656971.
[15] H.W. Yeung, N. Coe, Toward a dynamic theory of global production networks, Econ. Geogr. 91 (1) (2015) 29–58, https://doi.org/10.1111/ecge.12063.
[16] Y. Li, N.A. Phelps, Articulating China's science and technology: knowledge collaboration networks within and beyond the Yangtze River Delta megalopolis in China. Chinese Geogra, Science 28 (2) (2018) 247–260, https://doi.org/10.1007/s11769-018-0944-8.

[17] K. Martinus, T.J. Sigler, G. Searle, et al., Strategic globalizing centers and sub- network geometries: a social network analysis of multi-scalar energy networks, Geoforum (64) (2015) 78–89, https://doi.org/10.1016/j.geoforum.2015.06.006.
[18] M. Castells, The Rise of the Network Society, second ed., Wiley-Blackwell, Chichester, 2010 https://doi.org/10.1002/9781444319514.
[19] Z. Neal, Refining the air traffic approach to city networks, Urban Stud. 47 (10) (2010) 2195–2215, https://doi.org/10.1177/0042098009357352.
[20] B. Derudder, X. Liu, C. Kunaka, et al., The connectivity of South Asian cities in infrastructure networks, J. Maps 10 (1) (2014) 47–52, https://doi.org/10.1080/17445647.2013.858084.
[21] P.J. Taylor, B. Derudder, J. Faulconbridge, et al., Advanced producer service firms as strategic networks, global cities as strategic places, Econ. Geogr. 90 (3) (2014) 267–291, https://doi.org/10.1111/ecge.12040.
[22] C. Rozenblat, Opening the black box of agglomeration economies for measuring cities' competitiveness through international firm networks, Urban Stud. 47 (13) (2010) 2841–2865, https://doi.org/10.1177/0042098010377.
[23] X. Luo, M. Chen, Urban network of China from the perspective of population mobility: three-dimensional co-occurrence of nodes and links, Environ. Plann. 53 (5) (2021) 887–889, https://doi.org/10.1177/0308518X21997818.
[24] G. Zhang, H. Yuan, Spatio-temporal evolution characteristics and spatial differences in urban tourism network attention in China: based on the Baidu index, Sustainability 14 (20) (2022) 13252, https://doi.org/10.3390/su142013252.
[25] Y. Wei, W. Song, C. Xiu, et al., The rich-club phenomenon of China's population flow network during the country's spring festival, Appl. Geogr. 96 (2018) 77–85, https://doi.org/10.1016/j.apgeog.2018.05.009.
[26] D.E. Jelinski, J. Wu, The modifiable areal unit problem and implications for landscape ecology, Landsc. Ecol. 11 (3) (1996) 129–140, https://doi.org/10.1007/bf02447512.
[27] E. Swyngedouw, Neither global nor local: 'glocalization' and the politics of scale, in: K.R. Cox (Ed.), Spaces of Globalization: Reasserting the Power of the Local, Guilford Press, New York, 1997. ISBN 1-57230-199-6.
[28] P.J. Taylor, A materialist framework for political geography, Trans. Inst. Br. Geogr. 7 (1) (1982) 15–34, https://doi.org/10.2307/621909.
[29] M.P. Smith, Transnational Urbanism: Locating Globalization, Blackwell, Oxford, 2000. ISBN: 0 631 18424 4.
[30] P.J. Taylor, Is there a Europe of cities? World cities and the limitations of geographical scale analyses, in: E. Sheppard, R.B. McMaster (Eds.), Scale and Geographic Inquiry: Nature, Society, and Method, Blackwell, Oxford, 2004, pp. 213–235, https://doi.org/10.1002/9780470999141.
[31] K.R. Cox, Spaces of dependence, spaces of engagement and the politics of scale, or: looking for local politics, Polit. Geogr. 17 (1) (1998) 1–23, https://doi.org/10.1016/S0962-6298(97)00048-6.
[32] B. Jessop, N. Brenner, M. Jones, Theorizing sociospatial relations, Environ. Plann. D 26 (3) (2008) 389–401, https://doi.org/10.1068/d91.
[33] N. Brenner, The limits to scale? Methodological reflections on scalar structuration, Prog. Hum. Geogr. 25 (4) (2001) 591–614, https://doi.org/10.1191/030913201682688.
[34] A. Bank, B.H. Van, Transnational conflicts and the politics of scalar networks: evidence from Northern Africa, Third World Q. 28 (3) (2007) 593–612, https://doi.org/10.1080/01436590701193031.
[35] H. Leitner, The politics of scale and networks of spatial connectivity: transnational interurban networks and the rescaling of political governance in Europe, in: E. Sheppard, R.B. McMaster (Eds.), Scale and Geographic Inquiry: Nature, Society, and Method, 2004, pp. 236–255, https://doi.org/10.1002/9780470999141.ch12. Blackwell, Oxford.
[36] H. Bathelt, A. Malmberg, P. Maskell, Clusters and knowledge: local buzz, global pipelines and the process of knowledge creation, Prog. Hum. Geogr. 28 (1) (2004) 31–56, https://doi.org/10.1191/0309132504ph46.
[37] R. Boschma, Relatedness as driver of regional diversification: a research agenda, Reg. Stud. 51 (3) (2017), https://doi.org/10.1080/00343404.2016.1254767, 351-36.
[38] W. Zhang, Z. Chong, X. Li, et al., Spatial patterns and determinant factors of population flow networks in China: analysis on Tencent Location Big Data, Cities 99 (2020) 102640, https://doi.org/10.1016/j.cities.2020.102640.
[39] H. Meng, X. Huang, X. Mao, et al., The formation and proximity mechanism of population flow networks under multiple traffic in China, Cities 136 (2023) 104211, https://doi.org/10.1016/j.cities.2023.104211.
[40] S. Zhang, Q. Wang, Y. Wei, et al., Pattern evolution and localization of China's financial network based on different types of banks, Papers Appl. Geogr. 6 (4) (2020) 416–435, https://doi.org/10.1080/23754931.2020.1801493.
[41] Z. Neal, Differentiating centrality and power in the world city network, Urban Stud. 48 (13) (2011) 2733–2748, https://doi.org/10.1177/0042098010388954.
[42] T.J. Sigler, K. Martinus, Extending beyond 'world cities' in World City Network (WCN) research: urban positionality and economic linkages through the Australia-based corporate network, Environ. Plann. 49 (12) (2017) 2916–2937, https://doi.org/10.1177/0308518X16659478.
[43] W. Ma, Z. Fang, X. Zhang, Comparative analysis of structural characteristics of China's 18 typical urban agglomerations based on flows of various elements, Ecol. Model. 479 (2023) 110308, https://doi.org/10.1016/j.ecolmodel.2023.110308.
[44] X. Liu, B. Derudder, M. Wang, Polycentric urban development in China: a multi-scale analysis, Environ. Plann. B 45 (5) (2018) 953–972, https://doi.org/10.1177/2399808317690155.