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Spatial Distribution Characteristics and Strategies of Urban Agglomerations from a Spatiotemporal Perspective: An Empirical Analysis Based on the Nanjing Urban Agglomeration

Min Li[1,a], Lixuan Tang[1,b,*]

[1] *Nanhua University, 228 Hengqi Road, Zhengxiang District, Hengyang City, Hunan Province, China*
a. 1914485498@qq.com , b. 1085019606@qq.com
**corresponding author*

Abstract: This study selects nine cities within the Nanjing urban agglomeration. Based on the traditional gravity model, the study constructs an evaluation index system for assessing the comprehensive strength of cities, applies the entropy method to calculate the cities' overall strength, and uses an improved potential model to investigate the internal spatial structure and development relationships within the urban agglomeration. The results indicate that from 2010 to 2020, the southern region of the Nanjing urban agglomeration formed the strongest interaction zone. Nanjing exhibits a clear agglomeration effect, with some peripheral cities benefiting from its radiation effect, while Huai'an and Wuhu, located at the northern and southern ends of the agglomeration, lag in development and show relatively slow growth. Based on these findings, the study proposes a strategy for developing the Nanjing urban agglomeration into a hierarchical urban system of "one core, one sub-core, and three tiers" and a spatial structure of "one center, three circles, and four clusters," aiming to create an "imbalanced balance" in spatial distribution.

Keywords: Gravity model, potential model, urban spatial distribution, GIS, entropy method.

1. Introduction

An urban agglomeration refers to a collective entity formed within a certain regional space, centered around a megacity, and composed of cities of various levels, scales, and functions. It relies on a developed transportation network to attract and radiate to surrounding areas, creating a system of mutual interaction and aggregation. The spatial distribution of an urban agglomeration reflects its overall level of development and the economic and social interconnections between cities within the group. It serves as a measure of the agglomeration's competitiveness. Optimizing the spatial structure of urban agglomerations involves analyzing the limitations and potential of urban spatial development from a spatial perspective, based on the current state of spatial development. It also involves proposing future trends and a general framework for spatial development, making it an essential aspect of urban system research [1].

Currently, China has entered a critical period of development, where high-quality development is the primary task in building a modern socialist country. Promoting regional coordinated development

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is a key aspect of implementing new development concepts and achieving high-quality development. The report from the 20th National Congress of the Communist Party of China emphasizes the need to advance the development of the Yangtze River Economic Belt and the integration of the Yangtze River Delta. It calls for building a coordinated development pattern for cities of different sizes by relying on urban agglomerations. The high-quality development of the Nanjing urban agglomeration is a crucial component of both the Yangtze River Economic Belt and the Yangtze River Delta integration development strategy, as well as a key practice of the national new-type urbanization strategy.

Previous research has analyzed the spatial structure of urban agglomerations from various perspectives, but there is still room for methodological improvement. In terms of research content, most studies focus on the hierarchical structure of urban agglomerations, with relatively little attention paid to the spatial linkages between cities within the hierarchy. Furthermore, with the ongoing development of cities, the traditional gravity model, which relies on GDP and population data, may no longer fully reflect the comprehensive development of a city. Building on existing research, this study selects the Nanjing urban agglomeration as the research object, constructs an evaluation system, and applies the entropy method to derive comprehensive scores from the evaluation indicators. The modified gravity model and potential model are then used to assess the spatial distribution, contributing to the theoretical research on the spatial distribution of urban agglomerations.

2. Data Sources and Research Methods

2.1. Overview of the Study Area

The Nanjing urban agglomeration spans Jiangsu and Anhui provinces and serves as an important conduit for driving the development of central and western regions of China, holding a significant position in the national Yangtze River Economic Belt development strategy. The agglomeration exhibits a clear hierarchical scale, consisting of one megacity (Nanjing), four large cities (Wuhu, Yangzhou, Huai'an, Changzhou), two medium-sized cities (Zhenjiang, Ma'anshan), and two relatively small cities (Chuzhou, Xuancheng). The distinct levels and scales of these cities make this region an ideal subject for studying the spatial structure changes of metropolitan areas.

Within the Nanjing urban agglomeration, only Liyang City and Jintan District of Changzhou are included. However, due to the difficulty in obtaining district-level data and the small scale of these areas, they are not suitable for analyzing urban spatial distribution. Therefore, the entire city of Changzhou is included in this study.

2.2. Data Sources

Data used to measure the comprehensive quality of each city were obtained from the Jiangsu Statistical Yearbook, Anhui Statistical Yearbook, Nanjing Statistical Yearbook, as well as statistical yearbooks of the other eight prefecture-level cities. The study conducted cross-sectional analyses of the Nanjing urban agglomeration for the years 2010, 2015, and 2020, using five-year intervals.

Travel times between cities were determined based on the following principles: (1) Given the current dominance of long-distance rail transport, for cities with direct railway passenger stations, travel times were confirmed through the website https://www.12306.cn/index/. (2) For cities without direct railway connections, travel times were calculated based on transfers via intermediary stations, with the transfer time included [1].

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2.3. Research Methods

2.3.1. Construction of the Evaluation Index System

A city's comprehensive strength is determined by multiple factors, including its size, economy, and social aspects. Based on city comprehensive strength evaluation systems from various references, and in conjunction with the specific conditions of cities in the Nanjing urban agglomeration, eight indicators were selected from four dimensions: city size, economic strength, social life, and openness to the outside world, to construct the comprehensive strength evaluation index system for the cities in the Nanjing urban agglomeration (see Table 1). The selected indicator factors were standardized using the min-max normalization method, and the entropy method was applied to assign weights to each indicator factor, resulting in the weightings of the indicators (see Table 1).

Table 1: Nanjing Urban Agglomeration Comprehensive Strength Evaluation Index System

Indicator Category	Specific Indicators	Units	Explanation	Weight
City Scale	Urban Population	Ten thousand people	Population Scale	0.11
	Urban Built-up Area	Square kilometers	Spatial Development Capacity	0.12
Economic Strength	Regional GDP	Billion CNY	Economic Development Level	0.12
	Fixed Asset Investment	Billion CNY	Investment Level	0.11
Social Life	Enrolled Students in Higher Education Institutions	Ten thousand people	Quality of Social Education	0.14
	Health Institutions	count	Social Healthcare Level	0.14
Openness to the Outside World	Total Import and Export	Billion USD	Foreign Trade Level	0.13
	Actual Utilized Foreign Capital (FDI) Amount	Billion USD	Foreign Capital Attraction Level	0.12

2.3.2. Gravity Model

The typical gravity model is widely applied in urban economics and transportation geography. It is derived from Newton's law of universal gravitation, which posits that the interaction between two cities is proportional to their population sizes (representing the "mass" of the cities) and inversely proportional to the distance between them. The general form is as follows:

$$I_{ij} = k\frac{P_i P_j}{D_{ij}^{a}},$$

Where: I_{ij} is the interaction between cities I_i and I_j; α is the exponent measuring the friction of distance; k is the gravitational constant, typically set to 1; P_i and P_j represent the population sizes of cities i and j; D_{ij} is the distance between cities i and j. The gravity model is highly flexible. Besides using population size as a parameter, other factors can also be applied.

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With the expansion of city sizes and the spread of regional boundaries, the traditional gravity model for cities no longer meets current needs. Therefore, this study adopts eight indicators, including GDP, fixed asset investment, and total imports and exports, to measure the comprehensive strength of cities. Instead of using straight-line distance between cities, the travel time between two places is now used to more objectively and comprehensively reflect the intensity of interaction between cities. The process for adjusting the spatial gravity model is as follows [1]:

$$I_{ij} = k\frac{M_i M_j}{D_{ij}^{\alpha}} \tag{1}$$

Where: I_{ij} represents the intensity of spatial interaction between cities i and j; α is the exponent measuring the friction of distance, set to 2 in this study; k is the gravitational constant, set to 0.01 in this study; M_i and M_j represent the comprehensive strength coefficients of cities i and j; D_{ij} is the travel time between cities i and j.

2.3.3. Potential Model

The potential model is derived from the gravity model and is used to measure the total interaction capacity between any city and other cities within an urban agglomeration (including itself), known as the potential value. This study adopts the method proposed by Liu Meihua [3] to calculate the development potential values of each city. The formula is as follows:

$$V_i = \sum k_{ij} I_{ij} \tag{2}$$

$$k_{ij} = \frac{GDP_i}{GDP_i GDP_j} \tag{3}$$

Where: I_{ij} represents the spatial interaction strength between cities i and j derived from equation (1); V_i is the development potential value of city i; k_{ij} is the weight, which represents the contribution of city i to the I_{ij} value. Since the contributions of two interacting cities to the gravitational force between them are not equal, this factor must be considered when calculating potential. Here, GDP is used for the calculation.

3. Research Results and Analysis

3.1. Analysis of Comprehensive Strength Evaluation Results

The comprehensive strength scores (M) of the cities within the Nanjing urban agglomeration for the years 2010, 2015, and 2020 were obtained through weighting, and the cities were ranked accordingly by year, resulting in the comprehensive quality rankings of cities in the Nanjing urban agglomeration (see Figure 1).

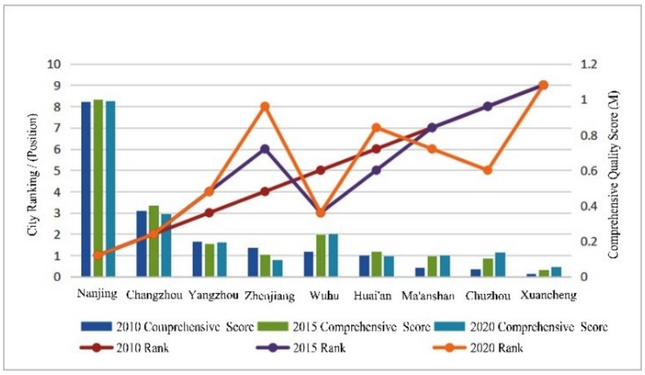

Figure 1: Ranking Changes of Comprehensive Quality in Nanjing Urban Agglomeration Cities

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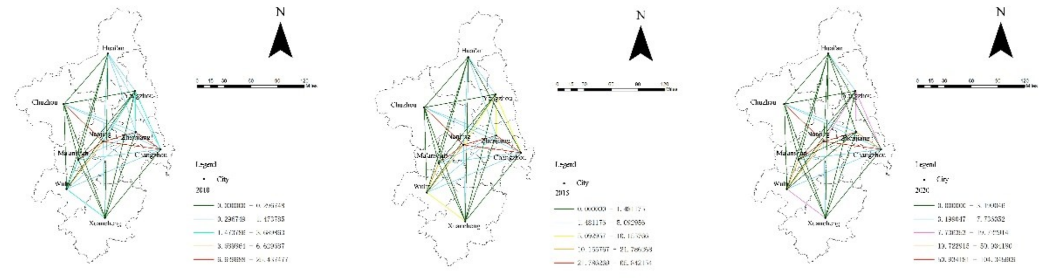
The comprehensive strength score is a relative value based on the results of the entropy method. It cannot be directly compared quantitatively but can be used to qualitatively describe the development level of each city over the years. Based on this, the evolution of the comprehensive strength of cities in the Nanjing urban agglomeration from 2010 to 2020 can be observed.

Starting in 2010, Nanjing's development trajectory began to emerge, and the core driving role of Nanjing became more pronounced after 2015. Aside from Nanjing, in the past decade, Changzhou and Wuxi have consistently ranked high in terms of comprehensive strength, with the surrounding areas showing overall improvement in development levels.

By 2020, the gap in comprehensive development levels between cities in the Nanjing urban agglomeration had narrowed compared to 2010. However, Huai'an and Xuancheng did not form highly developed dense areas like other regions, instead displaying a distinct core-periphery pattern, revealing unbalanced development characteristics.

3.2. Analysis of Spatial Linkage Measurement Results

The gravitational values between the nine cities in the Nanjing urban agglomeration, as well as the relationships between each city and the city with which it has the greatest gravitational attraction, were visualized using flight line maps in ArcGIS (see Figure 2). The width and color of the flight lines are used to distinguish the magnitude of gravitational values.



(a) Gravitational Distribution of the Nanjing Urban Agglomeration in 2010 (b) Gravitational Distribution of the Nanjing Urban Agglomeration in 2015 (c) Gravitational Distribution of the Nanjing Urban Agglomeration in 2020

Figure 2: Gravity Flight Lines of Nanjing Urban Agglomeration Cities

In 2010, the spatial connections among the cities in the Nanjing urban agglomeration showed characteristics of close central connections and balanced peripheral connections, with gravitational continuity throughout the region:

(1) The urban region formed by Nanjing, Yangzhou, Zhenjiang, and Changzhou was the area with the strongest spatial interaction, forming a web-like gravitational network.

(2) Wuxi, Ma'anshan, Chuzhou, and Huai'an, cities on the periphery of the Nanjing urban agglomeration, had relatively strong spatial interaction, forming a relatively balanced urban system in the northwest of the agglomeration.

(3) Huai'an and Xuancheng, located at the northern and southern ends of the Nanjing urban agglomeration, had the lowest gravitational interaction with Nanjing among all cities in the agglomeration.

In 2015, the central system of the Nanjing urban agglomeration further strengthened:

(1) The internal connections within the urban region formed by Nanjing, Yangzhou, Zhenjiang, and Changzhou weakened, with the direct connections between Yangzhou and Changzhou relatively diminishing.

(2) The internal connections within the urban region formed by Nanjing, Changzhou, Ma'anshan, and Chuzhou strengthened, with Nanjing's radiating influence as the central city increasing over more cities in the Nanjing urban agglomeration.

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By 2020, the central linkage area of the Nanjing urban agglomeration expanded from east to west, while the gravitational density at the northern and southern ends of the agglomeration remained insufficient. The spatial linkage of the Nanjing urban agglomeration had fully concentrated in Nanjing. The four city pairs with the strongest interaction in 2020 remained consistent with 2015, but there were some differences:

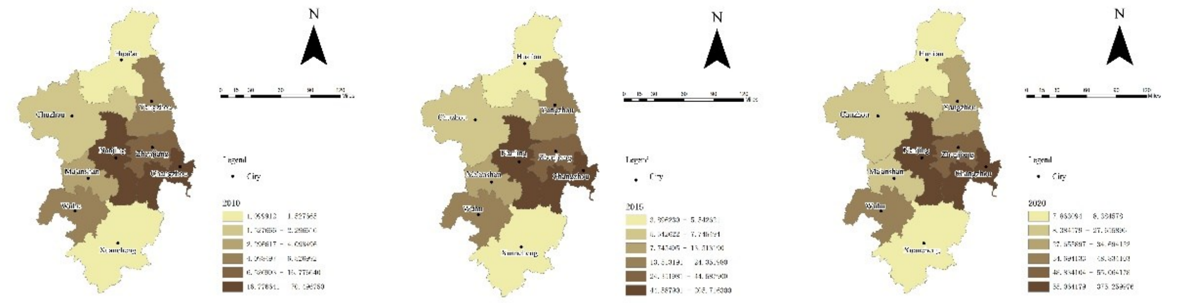
(1) Nanjing’s gravitational pull on cities in Anhui Province, such as Chuzhou, Ma’anshan, and Wuhu, further increased, gradually solidifying Nanjing’s position as the core city.

(2) The belt-shaped gravitational field between Nanjing, Changzhou, Chuzhou, Ma’anshan, and Wuhu was further reinforced, with the barrier effect of administrative boundaries significantly reduced.

(3) Huai’an’s attraction to the southern region further weakened, and there was a clear divergence in gravitational density between the central cities of the Nanjing urban agglomeration and the cities at the southern and northern ends.

3.3. Analysis of City Development Potential Measurement Results

The development potential values of the nine cities within the Nanjing urban agglomeration for the three time periods of 2010, 2015, and 2020 were visualized using ArcGIS software, and the results are shown (see Figure 3). Additionally, the potential values of each city were ranked by year, resulting in a ranking table of potential values for the cities in the Nanjing urban agglomeration (see Table 2).



(a) Potential Distribution of the Nanjing Urban Agglomeration in 2010 (b) Potential Distribution of the Nanjing Urban Agglomeration in 2015 (c) Potential Distribution of the Nanjing Urban Agglomeration in 2020

Figure 3: Potential Distribution Map of Nanjing Urban Agglomeration Cities (2010, 2015, 2020)

Table 2: Ranking Table of Potential Values of Cities in Nanjing Urban Agglomeration (2010, 2015, 2020)

	Nanjing	Changzhou	Zhenjiang	Yangzhou	Wuhu	Ma’anshan	Chuzhou	Huai’an	Xuancheng
2010 Rank	1	2	3	4	5	6	7	8	9
2015 Rank	1	2	3	5	4	6	7	8	9
2020 Rank	1	2	3	5	4	6	7	9	8

In 2010, the overall urban potential value of the Nanjing metropolitan area was relatively low, with a highly uneven distribution. The leading cities showed significant disparities compared to other cities, far exceeding them. The city with the highest potential value in 2010 was Nanjing, which, along with Changzhou, ranked in the first tier, significantly outperforming other cities in the Nanjing metropolitan area. The second tier contained only Zhenjiang, a city whose potential value needed improvement. Yangzhou, Ma’anshan, and Wuhu were in the third tier, exhibiting low urban potential values, while Huai’an, Chuzhou, and Xuancheng were in the fourth tier, with very low urban potential values.

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By 2015, the urban potential values of the Nanjing metropolitan area had improved, but only the cities in the first and second tiers showed significant increases. The radiation and agglomeration effects of Nanjing, as the central city, became more evident. In the 2015 urban potential values, Nanjing and Changzhou still occupied the first tier, with Nanjing showing a notable increase, ranking first, and the agglomeration effect starting to manifest. In the second tier, apart from Zhenjiang, Yangzhou and Wuhu were added, indicating that urban development was gradually spreading outward from the center. Ma'anshan and Chuzhou were placed in the third tier; both cities experienced some improvement, although the increase was not substantial. Huai'an and Xuancheng remained in the fourth tier, with Huai'an's potential value increasing more significantly than Xuancheng's.

In 2020, the overall urban potential values of the Nanjing metropolitan area rose, and the distribution structure remained consistent with that of 2015. The agglomeration effect of the central city became increasingly prominent, leading in development potential. In 2020, Nanjing and Changzhou, positioned in the first tier, widened their gap. Nanjing's status as a core city was further solidified. In the second tier, Zhenjiang saw a minor increase, lagging behind Yangzhou and Wuhu, with Wuhu experiencing a more noticeable improvement. Among the remaining cities in the third and fourth tiers, except for Huai'an, which had a slight increase, other cities also showed significant enhancements.

4. Conclusions and Discussion

4.1. Discussion and Reflection

The spatial distribution pattern of the Nanjing metropolitan area generally exhibits characteristics of uneven development between the center and the periphery. The gap between the central region and peripheral cities will persist; however, with the advancement of coordinated urbanization, differentiated regional development, and the integration of urban and rural development, the spatial structure of the Nanjing metropolitan area is revealing spatial connections and potential development areas in the northwest region.

Huai'an and Xuancheng both show considerable gaps in overall urban strength and mutual attractiveness compared to the central area cities, categorizing them as cities with weak spatial connections. In contrast, the remaining cities, especially Nanjing and Changzhou, exhibit a trend of high urban density and contiguous spatial development, categorizing them as cities with strong spatial connections. In the future, the inter-regional flow of factors in the Nanjing metropolitan area will continue to strengthen, with tighter spatial connections between the north and south, merging to form an unevenly "balanced" spatial distribution.

4.2. Main Conclusions and Strategies

The study indicates that the intensity of spatial connections in the Nanjing metropolitan area radiates outward from Nanjing, the core city, decreasing towards the north and south. The hierarchical distinctions among cities are clear, contributing to the overall stability of the metropolitan area. In terms of spatial structure, Nanjing has the highest attraction and potential values, placing it at the core of the spatial structure and dominating network resources. The entire metropolitan area can be divided into a hierarchy of "one core and one subsidiary with three secondary cities" and a structure of "one center, three circles, and four clusters."

Based on these conclusions, the following strategies for the spatial distribution of the Nanjing metropolitan area are proposed:

(1) Urban development can be classified into four levels based on attraction and potential values. The siphoning effect generated by Nanjing as the core city will naturally attract capital and population,

widening the development gap between cities in different tiers. Therefore, it is crucial to cultivate "bridge" cities between the core and peripheral cities. Based on the analysis of spatial connection strength and potential development, Changzhou can serve as the subsidiary core city. Other cities can be categorized as secondary central cities based on attraction and potential value tiers and spatial orientations, with Yangzhou, Wuhu, and Chuzhou identified, among which Chuzhou should be accelerated in its development to become a more influential city, enhancing its overall strength.

(2) According to the above classification of city levels, urban development can evolve into a structure of "one center, three circles, and four clusters." The development of the Nanjing metropolitan area requires substantial growth from each member; thus, establishing a cluster structure can support this development. Nanjing and Changzhou will be designated as the main central cluster in the southeastern position; Wuhu and Xuancheng will form the southwestern cluster; Chuzhou and Ma'anshan will establish the northwestern cluster; and Yangzhou, Zhenjiang, and Huai'an will make up the northeastern cluster.

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