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Original Paper

Analysis of Spatial Characteristics and Driving Factors of Urbanization Level in the Yangtze River Delta Region

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Abstract

The Yangtze River Delta Urban Agglomeration (YRD), a pivotal intersection of the "Belt and Road" Initiative and the Yangtze River Economic Belt, holds an irreplaceable strategic position in China's modernization and opening-up. With the issuance of "Five-Year Action Plan for In-depth Implementation of the People-Centered New Urbanization Strategy", scientifically assessing its urbanization quality and exploring driving factors have become increasingly critical. This study focuses on 41 cities in the YRD from 2014 to 2023, calculating urbanization levels via weighted nighttime light remote sensing data and POI data, analyzing spatial correlations using Exploratory Spatial Data Analysis (ESDA), and identifying driving factors through the Multi-scale Geographically and Temporally Weighted Regression (MGTWR) model. Results indicate that urbanization levels generally rose but with significant spatial disparities—higher in eastern cities and lower in western ones. The region exhibits positive spatial autocorrelation, with eastern cities forming high-high clusters and western cities low-low clusters. Seven factors, including investment in science and technology, highway density, and industrial structure advancement, exert heterogeneous driving effects. level of science and technology benefits southwest regions more, while highway density and population density strongly drive western cities. Per capita gross domestic product significantly boost central-southern and eastern regions, respectively, and industrial structure advancement positively impacts all cities. These findings provide a scientific basis for promoting high-quality integrated development of the YRD and offer references for other urban agglomerations.

Keywords

Urbanization Level, Exploratory Spatial Data Analysis (ESDA), Kernel Density Analysis; Multi-scale Geographically and Temporally Weighted Regression (MGTWR)

1. Introduction

Urbanization serves as a core indicator of a country's industrialization and modernization, reflecting economic vitality and social progress. Since China's reform and opening-up, urbanization has advanced through three phases: initial take-off driven by coastal development, rapid expansion emphasizing both scale and quality, and the current stage focusing on high-quality development. China's urbanization has taken a distinct and unique path, with factors such as the rapid growth of the national economy and economic globalization driving the rapid development of China's urbanization[1]. By 2023, China's permanent urban population reached 933 million, with an urbanization rate of 66.16%—still lagging behind the 80% average in developed countries, China's urbanization rate still has much room for improvement.

The YRD stands out as one of China's most urbanized regions, with a 2020 urbanization rate of 70.85%, well above the national average. From 2010 to 2020, its urban construction land expanded by approximately 40%, fueling economic growth but also triggering challenges such as cultivated land loss, environmental pollution, and inefficient land use. As a national strategic hub, the YRD's high-quality urbanization is pivotal for both regional development and national urbanization advancement. The 2024 Five-Year Action Plan for New Urbanization further underscores the need for balanced, people-centered urban development, making research on the YRD's urbanization characteristics and driving factors timely and imperative.

The YRD's strategic location at the intersection of the Yangtze River Economic Belt and coastal economic zones makes it a driver of national economic growth. Since the elevation of YRD integration to a national strategy in 2018, the region has achieved remarkable progress, but contradictions between development, resources, land, and the environment persist[2]. This study contributes theoretically by proposing a novel urbanization measurement method integrating multi-source data and applying the MGTWR model to capture spatio-temporal heterogeneity. Practically, it provides decision-makers with targeted recommendations to optimize urbanization quality, narrow regional gaps, and promote coordinated development—aligning with "Three-Year Action Plan for Integrated Development of the Yangtze River Delta Region (2024-2026)".

2. Literature Review

2.1 Studies on Urbanization Level

Scholars worldwide have explored urbanization from diverse perspectives. Huang (2014) emphasized the need for China to shift from an extensive to an intensive urbanization model[3]. Tan et al. (2005) analyzed urban land expansion in the Beijing-Tianjin-Hebei region, highlighting regional disparities[4]. Seto et al. (2011) noted that global urban land expansion outpaces population growth, with China among the fastest-expanding regions[5]. A study by Schneider et al. (2014) examined the evolution of urban areas in China and found that from 1978 to 2010, the urban scale doubled. Large agglomeration areas were the main consumers of land in coastal and western regions. Although China's urbanization is closely related to large cities, the growth of urbanization in small and medium-sized cities was more significant during the period 2000-2010[6]. Domestic studies, Fang Chuanglin (2019) explored the importance of steady development in the process of advancing new urbanization and proposed key paths for promoting the future high-quality development of China's new urbanization[7]. Li Jianbao et al. (2021) explored the spatiotemporal pattern of the coupling coordination degree between population urbanization, energy consumption, and CO_2 emissions in Jiangsu Province from 2006 to 2017. They found significant regional differences: the coupling coordination degree was the highest in the eastern part, followed by the western part, and the southern part had a higher coupling coordination degree than the northern part, with the overall spatial pattern being relatively stable[8].

2.2 Measurement of Urbanization Level

Traditional measurement methods include single core indicator evaluation method (e.g., urban population ratio) and multi-index analysis method. Single core indicator evaluation method, while simple, fail to capture the complexity of urbanization, prompting the adoption of multi-index analysis method (Chen et al., 2010[9]; Lv et al., 2019[10]) and entropy method (Wang et al., 2012[11]; Wang et al., 2013[12]). With advancements in remote sensing and big data, scholars increasingly use multi-source data—such as nighttime light imagery (Lin et al., 2019[13]; Liu et al., 2024[14]) and POI data (Yao et al., 2017[15]; Meng et al., 2025[16])—to improve measurement accuracy. Tang et al. (2024) comprehensively used multi-source big data such as night-time lights, POI, and OSM road networks to identify urban built-up areas in urban agglomerations[17]. However, existing studies often rely on single data sources, limiting comprehensiveness.

2.3 Spatial Characteristics of Urbanization

Spatial studies have identified distinct patterns: Xue et al. (2010) found that the comprehensive urbanization level of China's cities is high in the Northeast region and low in the Southwest region, showing a decreasing trend from the Northeast to the Southwest. Cities with a relatively high urbanization level are spatially close to each other, forming several high-value agglomerations of urbanization level[18], while Zhang et al. (2014) noted faster land than population urbanization[19]. For the YRD, Xu et al. (2021) found the center of gravity of the Yangtze River Delta urban agglomeration is relatively stable, always near the coast of Taihu Lake within Suzhou City, showing a trend of moving towards the southeast direction.[20]. However, few studies have systematically analyzed spatial agglomeration and evolution using ESDA, particularly regarding local spatial autocorrelation.

2.4 Driving Factors of Urbanization

Driving factors include economic development (GDP, industrial structure), social factors (population density, income), and infrastructure (road density, technology). Guo et al. (2024) highlighted the expansion of local debt has a non-linear impact on urbanization, first promoting and then inhibiting it. In the early stage of debt expansion, it is conducive to improving urban infrastructure, mainly by raising the housing price-to-income ratio and stimulating fixed-asset investment to promote urbanization[21], while Lin et al. (2015) identified residential land expansion as a key driver[22]. Methodologically, panel data models (Xu et al., 2015[23]), GWR (Liu et al., 2023[24]), and GTWR (Cai et al., 2020[25]) are commonly used. However, GTWR assumes uniform bandwidths for all variables, ignoring multi-scale effects—an issue addressed by the MGTWR model, which remains underutilized in YRD urbanization research.

2.5 Literature Gaps

Existing studies lack a comprehensive measurement integrating nighttime light and POI data, rarely explore spatial effects via ESDA's semi-variogram/covariance cloud analysis, and seldom apply MGTWR to capture multi-scale spatio-temporal heterogeneity. This study addresses these gaps by proposing a human activity-intensive urbanization indicator, using ESDA to verify spatial correlations, and employing MGTWR to identify driving factors.

3. Research Object and Methods

3.1 Research Object

On the basis of the relevant theories of urbanization, focusing on the concept of new urbanization, this paper comprehensively measures the urbanization level of the Yangtze River Delta urban agglomeration using two aspects: night-time light index and urban POI data, explores the agglomeration of urbanization levels in different cities in the region from both temporal and spatial perspectives, and studies its temporal evolution characteristics. It studies the driving factors of urbanization in the Yangtze River Delta urban agglomeration, analyzes the main driving factors affecting the level of urbanization development, and based on this conclusion, provides theoretical basis and policy suggestions for the high-quality development of urbanization in the Yangtze River Delta region, so as to promote the coordinated development of urbanization in the region.

3.2 Research Methods

Literature Review: This method is used to synthesize theories, methods and gaps in urbanization research and perfect the shortcomings of existing research.

Empirical Analysis: This method is used to process multi-source data, measure urbanization, and analyze the spatial characteristics and driving factors of urbanization with the help of exploratory spatial data analysis methods and multi-scale spatiotemporal geographically weighted regression models.

ESDA: This method is mainly used to explore whether data exhibit patterns of clustering, dispersion, or random distribution in space, including global spatial autocorrelation and local spatial autocorrelation analysis. It is widely applied in fields such as socio-economic research and urban planning.

Kernel Density Estimation: Kernel density estimation is a non-parametric statistical method used to estimate the probability density function of a random variable. It can help understand the distribution characteristics of data and identify the clustering characteristics and trends of data.

MGTWR: MGTWR is a further extension of the geographically weighted regression method. It combines spatial and temporal dimensions, considering not only the heterogeneity in geographical locations but also the changes in the temporal dimension and the relationships between influencing factors at multiple scales. It can identify the degree of influence of influencing factors at different scales on geographical phenomena and can more comprehensively describe the complexity of phenomena.

4. Paper Structure and Innovations

4.1 Structure

Chapter 1: Introduction background, significance, literature review and methods.

Chapter 2: Conceptual and theoretical framework including urbanization definition, theories, methods.

Chapter 3: Overview of the YRD including geography, economy, policy and urbanization status.

Chapter 4: Measurement and spatial-temporal analysis of urbanization.

Chapter 5: Driving factors analysis using MGTWR.

Chapter 6: Conclusions, recommendations, and limitations.

4.2 Innovations

Novel Urbanization Indicator: Defines urbanization as human activity intensity, measured via weighted nighttime light and POI data using kernel density estimation.

Comprehensive Spatial Analysis: Uses ESDA,semi-variogram and trend analysis to verify spatial correlations and agglomeration.

Advanced Modeling: Applies MGTWR to capture multi-scale spatio-temporal heterogeneity, improving accuracy over GWR and GTWR.

5. Conceptual Definition, Theories, and Methods

5.1 Conceptual Definition

5.1.1 Urbanization

Urbanization refers to the transition from rural to urban societies, involving population migration, land use transformation, and economic restructuring. Traditional definitions focus on population or land, but this study proposes a new indicator for measuring urbanization, namely the intensity of human activities within a region. For any piece of land, the closer the communication activities among people are, the higher the level of urbanization.

5.1.2 POI Data

POI (Point of Interest) data includes 18 categories such as catering, finance, transportation and so on, coming from the Gaode Map database, reflecting urban functions and human activity. For example, in a certain region, if there are many points of interest in financial services such as banking and securities industries, it indicates that the financial level of that region is relatively high.

5.2 Theoretical Foundations

5.2.1 First Law of Geography

Proposed by Walter Christaller, it states that the spatial distribution of things is often not random but follows certain rules and patterns. Also, the distance between different locations can affect people's behaviors and activities. Generally, the connections between locations that are close to each other are more intimate. Finally resources, population, and economic activities often tend to concentrate in certain regions rather than being evenly distributed, and this concentration is often constrained by factors such as transportation and the environment. The theory supports spatial autocorrelation analysis.

5.2.2 The Theory of Regional Imbalance in Urbanization Development

It points out that the urbanization process does not unfold uniformly in space, but rather exhibits significant heterogeneous characteristics. This spatial differentiation stems from the differential allocation of multiple factors such as resource endowments, policy orientations, and technological innovation capabilities. Urbanization is spatially heterogeneous due to differences in resource endowments, policies, and innovation. Developed regions will attract the continuous agglomeration of production factors, thereby creating a development gap with underdeveloped regions. The "east-high and west-low" urbanization pattern in the Yangtze River Delta region is a typical manifestation of this theory.

5.2.3 Driving Mechanism of Urbanization

Urbanization is driven by three subsystems:

Industrial Upgrading: Shifting from primary to secondary/tertiary industries, boosting efficiency and capital accumulation.

Population Migration: Income and welfare gaps attract rural labor to cities, expanding consumer markets.

Infrastructure Improvement: Enhanced transportation and public services reduce transaction costs, fostering innovation and industrial upgrading.

5.3 Research Methods

5.3.1 Kernel Density Estimation

As a non-parametric method to estimate data distribution, it will take any point in the region as the center and set a regular region with a fixed bandwidth. Within this region, weights are assigned based on the distance between each point and the center point, with points closer in distance having higher weights. Ultimately, the estimated density of each point is the sum of the weighted densities of all points within this region. The Gaussian kernel function is used:

$$D = \frac{1}{nh}\sum_{i=1}^{n}\left[K*\left(\frac{s_i - x}{h}\right)\right] \tag{1}$$

where K is the Gaussian kernel (this paper selects the Gaussian kernel function as the kernel function for kernel density estimation), h is the bandwidth, si is any point within the region, x is any variable within the sample, si-x is the distance between two points, where the distance between the two points is less than the bandwidth, and n are total number of sample points.

5.3.2 Exploratory Spatial Data Analysis (ESDA)

Global Moran’s I: Measures overall spatial autocorrelation:

$$I = \frac{n}{S_0} \times \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\left(y_i - \bar{y}\right)\left(y_j - \bar{y}\right)}{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2} \tag{2}$$

Where n is total number of cities, yi is the urbanization level index of i-city, wij is spatial weight value.

$$S_0 = \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}$$

Local Moran's I:

$$I_i = \frac{y_i - \bar{y}}{\frac{1}{n}\sum\left(y_i - \bar{y}\right)^2}\sum_{j\neq i}^{n} w_{ij}\left(y_j - \bar{y}\right) \quad (3)$$

Where wij is spatial weight value, Ii is local Moran's index, yi is the urbanization level index of i-city. Affect the positive or negative sign of the local regression coefficient is related to $y_i - \bar{y}, \sum_{j\neq i}^{n} w_{ij}\left(y_j - \bar{y}\right)$,

suppose $z_{ij} = \sum_{j\neq i}^{n} w_{ij}\left(y_j - \bar{y}\right)$

Table 1. Meanings of Local Moran's Index

$y_i - \bar{y}$	z_{ij}	I_i	*meaning*	*agglomeration*
>0	*>0*	*>0*	*The urbanization level of this region is high, and the urbanization level of the surrounding areas is also high.*	*HH*
>0	*<0*	*<0*	*The urbanization level of this region is high, while that of the surrounding areas is low.*	*HL*
<0	*>0*	*<0*	*The urbanization level of this region is low, while that of the surrounding areas is high.*	*LH*
<0	*<0*	*>0*	*The urbanization level of this region is low, and the urbanization level of the surrounding areas is also low.*	*LL*

5.3.3 Geographically Weighted Regression

GWR: Captures spatial heterogeneity by embedding location into regression coefficients:

$$y_i = \beta_0\left(u_i, v_i\right) + \sum_{k=1}^{n}\beta_k\left(u_i, v_i\right)x_{ik} + \varepsilon_i \quad (4)$$

Where x_{ik} is the k-th control variable at that position, and $\beta_k\left(u_i, v_i\right)$ is the k-th regression coefficient for the i-th observation.

MGWR: The Geographically Weighted Regression model assumes that the spatial scale of each variable is the same, but this is not entirely the case. Therefore, the Multiscale Geographically Weighted Regression model takes into account the differentiated heterogeneous scales among variables, allowing each variable to have its own spatial level.

MGTWR: On the basis of the geographically weighted regression model, integrate the time dimension and set independent bandwidths for each explanatory variable to improve the model's goodness of fit:

$$UI_i = \beta_{bwt_0 s_0}\left(u_i, v_i, t_i\right) + \sum_{k=1}^{7}\beta_{bwt_k s_k}\left(u_i, v_i, t_i\right)x_{ik} + \varepsilon_i \quad (5)$$

Where UI_i is urbanization level index, x_{ik} is controlled variable, are Tech,RD,PD,Pw,Pgdp FDI,RD respectively, $\beta_{bwt_k s_k}(u_i, v_i, t_i)$ is the regression coefficient of location (u_i, v_i, t_i) based on spatial bandwidth bws_0 and temporal bandwith bwt_0.

6. Overview of the Yangtze River Delta Region

6.1 Regional Scope and Geography

The YRD covers 358,000 km² (3.7% of China's land) across Shanghai, Jiangsu, Zhejiang, and Anhui, with a subtropical monsoon climate—abundant rainfall, fertile plains, and dense river networks (e.g., Yangtze River, Taihu Lake). Topography varies: plains in Shanghai/Jiangsu, hills in Zhejiang, and plains/hills in Anhui.

6.2 Socio-Economic and Policy Context

6.2.1 Socio-Economic Development

The YRD is China's economic engine, contributing 24% of national GDP with 4% of land and 17% of population. By 2023, its GDP exceeded 30 trillion yuan and it has 9 cities with a GDP of over one trillion yuan, and this number ranks first among all urban agglomerations in the country. Public service facilities such as education, medical care, and culture in the Yangtze River Delta region are at a leading level in the country. Well-known universities like Shanghai Jiao Tong University, Fudan University, Zhejiang University, and Nanjing University provide strong talent support for regional development.

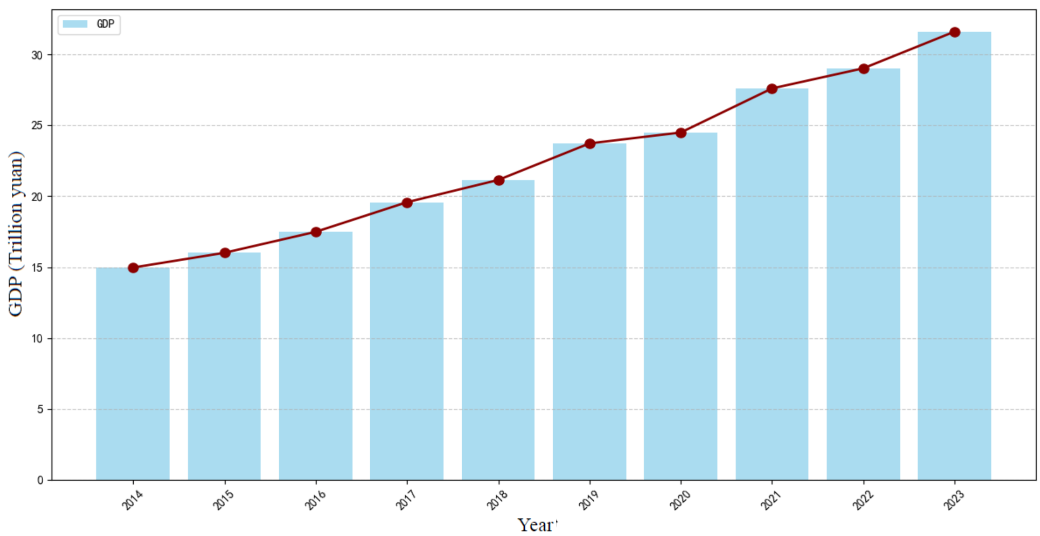


Figure 1. Gross Domestic Product of the Yangtze River Delta Region from 2014 to 2023

6.2.2 Policy Support

Key policies include the "Yangtze River Delta Integration Development Plan" published by State Council and "Three-Year Action Plan for Integrated Development of the Yangtze River Delta Region (2024 - 2026)", focusing on infrastructure connectivity, industrial synergy, and public service integration.

Coordination mechanisms—such as the Yangtze River Delta Regional Cooperation Office—facilitate cross-regional collaboration.

6.3 Current Status of Urbanization

6.3.1 High Urbanization Rate with Disparities

The 2020 urbanization rate was 70.85% (Shanghai: 89.3%, Jiangsu: 73.4%, Zhejiang: 72.2%, Anhui: 58.3%). Eastern cities (Shanghai, Suzhou, Hangzhou) are highly urbanized, while western Anhui (Huangshan, Chizhou) lags.

6.3.2 Outstanding Advantages

Population Agglomeration: Urban population reached 170 million in 2022, the population in the Yangtze River Delta region generally shows an increasing trend, and the attractiveness to the labor force continues is increasing.

Infrastructure Leadership: The railway operating mileage in the Yangtze River Delta region exceeds 13,000 kilometers, among which the high-speed railway mileage exceeds 6,500 kilometers, accounting for 16% of the national total, covering more than 95% of the prefecture-level cities in the region. The total length of the expressway network in the Yangtze River Delta region is approximately 16,000 kilometers, with land areas achieving expressway access to every county. According to the plan, by 2025, the density of expressways will reach 500 kilometers per 10,000 square kilometers.

Industrial Strength: The Yangtze River Delta is an important production base for new energy vehicles in China, and the photovoltaic industry has significant advantages in technological research and development as well as production and manufacturing. It has prominent advantages in advanced manufacturing: strategic emerging industries such as equipment manufacturing and the new generation of information technology are showing a trend of clustered development, such as the Lin-gang Special Area in Shanghai.

Trade Hub: Mechanical and electrical products are the largest export category in the Yangtze River Delta region. In 2024, the export of mechanical and electrical products reached 5.9 trillion yuan, accounting for 39.4% of the country's exports of similar products. In 2024, the export of high-end equipment reached 261.16 billion yuan, accounting for more than half of the country's exports of similar products, reaching 56.7%.

6.3.3 Existing Problems

Economically developed regions such as Shanghai and Hangzhou have a high level of urbanization but relatively weak radiation effects, which cannot fully drive the rapid development of surrounding cities, leading to imbalances in urbanization development across different regions. In the process of urbanization, the integration between urban and rural areas is insufficient, with townships and counties being relatively underdeveloped and having a large gap with central cities. Problems such as air pollution and water pollution caused by urban development are particularly prominent, and issues like tight land resources and inefficient land use are widespread.

7. Measurement and Spatial-Temporal Analysis of Urbanization Level

7.1 Data Processing

7.1.1 Nighttime Light Data

Data are from VIIRS VNL v2.2 (https://eogdata.mines.edu) (1) Economically developed regions such as Shanghai and Hangzhou have a high level of urbanization but relatively weak radiation effects, which cannot fully drive the rapid development of surrounding cities, leading to imbalances in urbanization development across different regions. In the process of urbanization, the integration between urban and rural areas is insufficient, with townships and counties being relatively underdeveloped and having a large gap with central cities. Problems such as air pollution and water pollution caused by urban development are particularly prominent, and issues like tight land resources and inefficient land use are widespread. (2) In VNL v2 and v2.1, the median calculation does not include months with fewer than 3 cloud-free coverage areas. However, v2.2 includes any month with multiple cloud-free coverage areas. (3) n VNL v2 and v2.1, the median calculation does not include months with fewer than 3 cloud-free coverage areas. However, v2.2 includes any month with multiple cloud-free coverage areas.

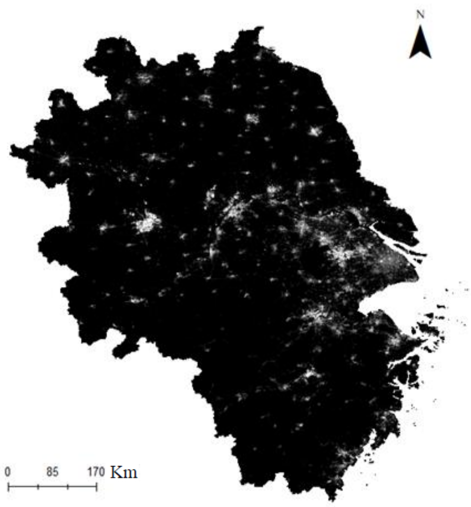


Figure 2. Light Intensity of the Yangtze River Delta Urban Agglomeration in 2023

7.1.2 POI Data

POI data is from Amap. To analyze urban POI data using the kernel density analysis method, first, download the administrative divisions of 41 cities in the Yangtze River Delta from the National Geospatial Information Public Service Platform. Amap POI data in 2014-2023 was cleaned (duplicates, outliers removed) and filtered to 18 urban-related categories. Kernel density estimation was applied in ArcGIS 10.8, with a threshold of 100 to exclude non-urban areas. Next, we crawl point of interest data through the open API of Amap, filter categories related to urbanization functions, and import the filtered data and shp map files into ArcMap 10.8. The point of interest data includes longitude and latitude coordinates. Then, using the kernel density analysis method, we obtain the kernel density values of the Yangtze River Delta urban agglomeration.

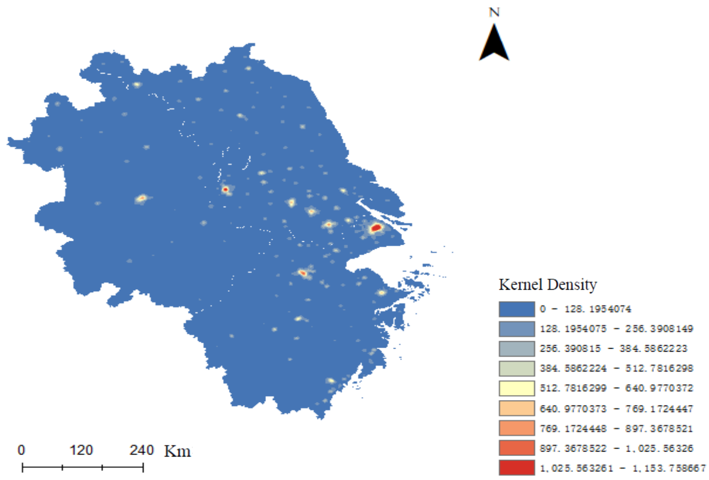


Figure 3. Kernel Density Values of the Yangtze River Delta Urban Agglomeration in 2023

7.2 Measurement of Urbanization Level

Urbanization level was calculated by weighting nighttime light intensity and POI kernel density equally. Taking Shanghai as an example, there are multiple pixel points within the Shanghai area. The intensity value corresponding to each pixel point is obtained by weighting the light intensity and the POI kernel density. The intensity of all pixel points within the Shanghai area is the urbanization level of Shanghai. It is considered that a night-time light intensity value greater than 12 reflects the intensity value of urban functional areas, so the night-time light threshold is also set to 12 in this section. According to the kernel density estimation map of the Yangtze River Delta urban agglomeration, it is assumed that a kernel density less than 100 does not belong to the scope of urban functional areas, so the kernel density estimation value threshold is set to 100:

$$UI = \log_{10} \sum_{j=1} \left(DN_{ij} + P_{ij} \right) * S_j \qquad DN_{ij} \geq 12, P_{ij} \geq 100 \tag{5}$$

The urbanization level index of the final Yangtze River Delta urban agglomeration is shown in Table 7.3. To unify the urbanization indices of all cities, a logarithmic transformation was applied to the indices.

Table 2. Urbanization Level Index

City	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Shanghai	5.654	5.669	5.668	5.716	5.705	5.724	5.731	5.746	5.743	5.774
Nanjing	5.085	5.071	5.108	5.153	5.178	5.231	5.268	5.310	5.312	5.344
Wuxi	4.999	4.982	5.026	5.070	5.093	5.115	5.143	5.192	5.194	5.240
Xuzhou	4.608	4.623	4.658	4.696	4.734	4.783	4.843	4.862	4.895	4.944
Changzhou	4.792	4.781	4.852	4.867	4.917	4.946	5.016	5.044	5.046	5.092
Suzhou	5.461	5.491	5.505	5.541	5.555	5.570	5.596	5.622	5.620	5.659
Nantong	4.861	4.899	4.917	4.960	5.000	5.049	5.072	5.061	5.062	5.128

Lianyungang	4.381	4.399	4.467	4.560	4.581	4.566	4.602	4.668	4.720	4.833
Huaian	4.475	4.469	4.494	4.588	4.627	4.668	4.744	4.779	4.798	4.848
Yancheng	4.474	4.620	4.694	4.777	4.865	4.891	4.950	4.958	4.946	4.970
Yangzhou	4.530	4.577	4.654	4.694	4.757	4.787	4.818	4.877	4.873	4.927
Zhenjiang	4.547	4.536	4.615	4.684	4.728	4.726	4.734	4.727	4.693	4.712
Taizhou	4.480	4.502	4.582	4.683	4.754	4.768	4.807	4.808	4.807	4.872
Suqian	4.182	4.190	4.384	4.410	4.475	4.551	4.626	4.652	4.613	4.684
Hangzhou	5.070	5.079	5.167	5.253	5.261	5.293	5.343	5.372	5.372	5.455
Ningbo	5.197	5.219	5.222	5.294	5.275	5.308	5.368	5.394	5.406	5.467
Wenzhou	4.759	4.748	4.785	4.918	4.893	4.951	4.988	5.113	5.111	5.204
Jiaxing	4.470	4.576	4.610	4.708	4.782	4.851	4.979	5.050	5.078	5.153
Huzhou	4.152	4.251	4.296	4.444	4.515	4.557	4.656	4.732	4.734	4.832
Shaoxing	4.578	4.593	4.618	4.732	4.726	4.761	4.863	4.893	4.904	4.985
Jinhua	4.728	4.748	4.860	4.909	4.963	4.993	5.046	5.064	5.078	5.173
Quzhou	3.594	3.675	3.791	3.905	3.915	3.982	4.095	4.231	4.247	4.347
Zhoushan	4.118	4.153	4.146	4.225	4.266	4.389	4.583	4.635	4.691	4.748
Taizhou	4.638	4.658	4.668	4.776	4.761	4.780	4.803	4.869	4.884	4.979
Lishui	4.039	4.044	4.121	4.189	4.167	4.243	4.218	4.310	4.343	4.410
Hefei	5.005	5.007	5.062	5.128	5.144	5.186	5.217	5.260	5.332	5.332
Wuhu	4.323	4.344	4.447	4.467	4.485	4.497	4.484	4.536	4.565	4.698
Bengbu	4.230	4.342	4.413	4.406	4.436	4.450	4.455	4.480	4.459	4.352
Huainan	3.904	3.933	3.970	4.038	4.102	4.179	4.178	4.195	4.262	4.294
Maanshan	4.330	4.332	4.369	4.402	4.414	4.404	4.401	4.400	4.383	4.434
Huaibei	3.911	3.853	3.985	4.023	4.087	4.175	4.293	4.341	4.236	4.029
Tongling	3.772	3.690	3.836	3.899	3.893	3.903	3.983	4.009	3.972	4.001
Anqing	3.987	4.000	4.095	4.194	4.263	4.313	4.358	4.447	4.451	4.577
Huangshan	2.980	3.001	2.819	2.918	2.920	3.019	3.101	3.195	3.204	3.250
Chuzhou	4.304	4.368	4.441	4.536	4.602	4.668	4.695	4.737	4.773	4.809
Fuyang	4.205	4.270	4.361	4.469	4.596	4.690	4.725	4.728	4.719	4.758
Suzhou	4.087	4.110	4.091	4.064	4.149	4.335	4.398	4.430	4.390	4.432
Liuan	3.861	3.905	4.069	4.211	4.282	4.430	4.496	4.512	4.502	4.503
Haozhou	3.958	4.016	4.094	4.324	4.462	4.486	4.506	4.490	4.163	4.255
Chizhou	3.383	3.293	3.431	3.472	3.469	3.517	3.540	3.599	3.662	3.869
Xuancheng	3.411	3.401	3.522	3.466	3.488	3.582	3.634	3.597	3.640	3.744
Urban agglomeration	6.330	6.349	6.386	6.447	6.468	6.502	6.542	6.574	6.579	6.631

The measurement results show that in 2023, among the cities in the Yangtze River Delta region, Shanghai had the highest urbanization level (5.774), while Huangshan had the lowest (3.25).

7.3 Temporal Evolution Characteristics

7.3.1 Overall Upward Trend

The YRD's average urbanization index rose from 6.330 (2014) to 6.631 (2023), with slower growth in 2022. Fast-growing cities include Quzhou (+0.753), Suqian (+0.502), and Lishui (+0.371), while Huaibei (-0.212) and Bengbu (-0.101) declined.

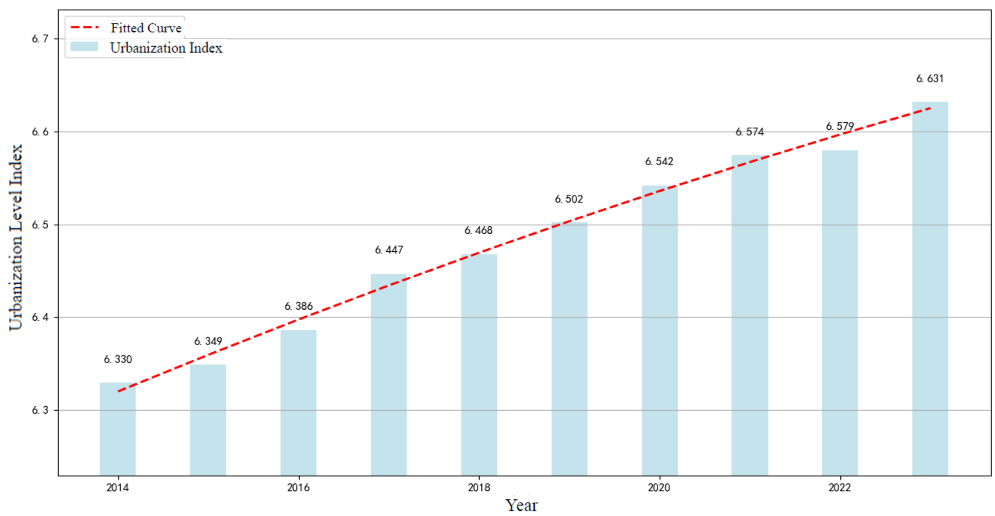


Figure 4. Time Trend of Urbanization Index in Urban Agglomerations

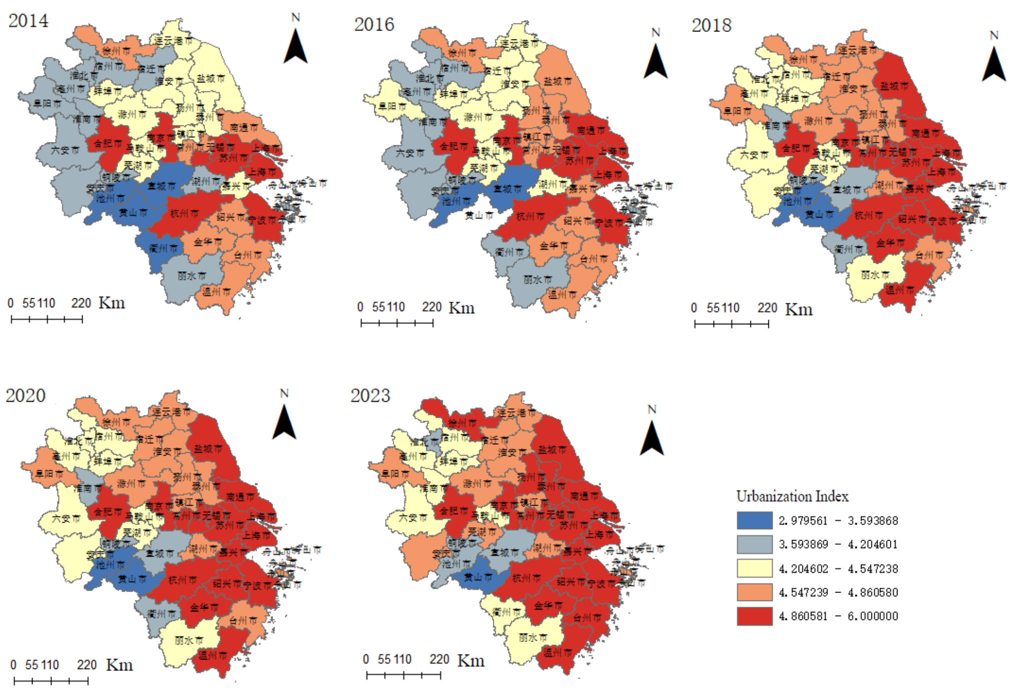


Figure 5. Analysis of the Temporal Evolution of the Urbanization Index

7.3.2 Convergence of Imbalances

Coefficients of variation decreased for most cities—e.g., Quzhou (-50.9%), Suqian (-59.0%)—indicating reduced internal disparities. However, Anhui cities (Huangshan: 13.69, Bozhou: 8.12) remain imbalanced.

7.4 Spatial Analysis

7.4.1 Spatial Distribution and Trend

The 2023 urbanization index has a mean of 4.76, standard deviation of 0.529, Skewness -0.545, Kurtosis 3.371, 1/4 quantile 4.427and a west-east upward trend, confirming higher urbanization in eastern coastal areas.

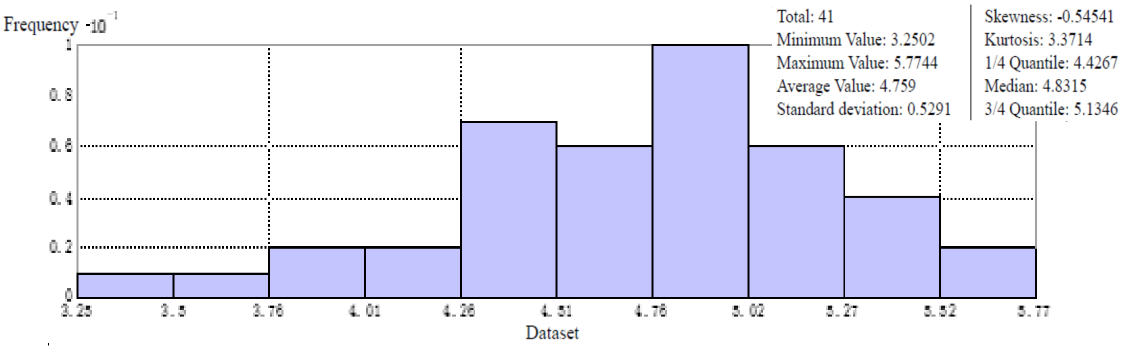
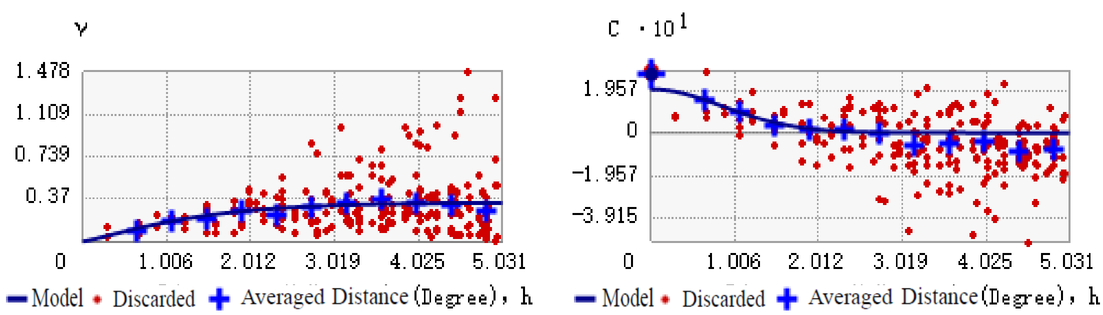


Figure 6. Histogram of Urbanization Index Distribution in 2023

7.4.2 Spatial Autocorrelation

Global Moran's I: Positive and increasing (2014: 0.301; 2023: 0.355), indicating strengthening spatial agglomeration.



a b

Figure 7. Semivariogram/Covariance Cloud

Semi-variogram Analysis: Shows spatial dependence, with distance-related variability.

7.4.3 Local Spatial Agglomeration

High-High (HH) Clusters: Concentrated in eastern cities (Shanghai, Suzhou, Ningbo), expanding to Huzhou and Shaoxing by 2023.

Low-Low (LL) Clusters: Stable in western Anhui (Huangshan, Anqing, Chizhou).

High-Low (HL) Clusters: Hangzhou (2014-2018) and Hefei (2023).

Low-High (LH) Clusters: Only Zhoushan.

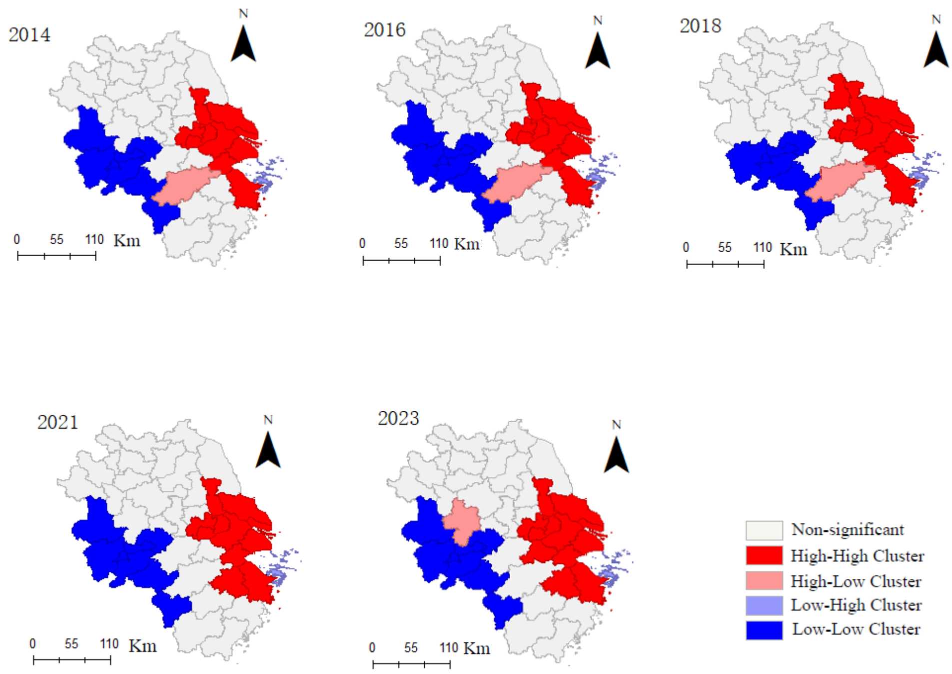


Figure 8. Local Clustering Map of Urbanization Index

8. Driving Factors Analysis Based on MGTWR Model

8.1 Selection of Driving Factors

This chapter selects data from three dimensions to analyze the driving factors of the urbanization level in the Yangtze River Delta region.:

City-specific: Highway density, level of science and technology.

Social: Population density, average wage of on-the-job employees.

Economic: GDP per capita, Foreign investment, industrial structure advancement.

8.2 MGTWR Model Construction

8.2.1 Model Specification

The MGTWR model uses Gaussian kernel functions and variable bandwidths. The AIC and BIC criteria of the MGTWR model are both smaller than those of other models, and the R^2 is larger, indicating that the MGTWR model has a better fit. It outperforms GWR, MGWR, and GTWR (lower AIC: -1318.615; higher R^2: 0.999).

8.2.2 Model Comparison

Model Comparison

Model	AIC	BIC	R2	adj_R2
GWR Model	-498.500	-542.123	0.961	0.956
MGWR Model	-1161.689	-1488.054	0.997	0.994
GTWR Model	-910.464	-1165.469	0.993	0.988
MGTWR Model	-1318.615	-1862.725	0.999	0.995

8.3 Analysis of Results

8.3.1 Investment in Science and Technology (TECH)

Positive driving effect for most cities, stronger in the southwest such as Liuan, Anqing, Lishui.

Weaker effects in the northeast due to mature infrastructure.

8.3.2 Highway Density (RD)

Significant positive effects in western cities such as Chizhou, Huangshan.

Negative/insignificant effects in eastern cities due to overcrowding.

8.3.3 Population Density (PD)

Strengthening positive effects over time, concentrated in western cities.

Weak effects in northern cities due to population outflow.

8.3.4 Residents' income level (PW)

Positive effects in southern Anhui and southwest Zhejiang.

Insignificant in northeastern YRD and northern Zhejiang.

8.3.5 Per Capita GDP (PGDP)

Increasingly significant positive effects, strongest in central-southern regions.

8.3.6 Foreign investment (FDI)

Strongest positive effects in eastern cities.

Negative effects in western Anhui.

8.3.7 Industrial Structure Advancement (ASI)

Universal positive effects, strengthening in eastern cities.

8.4 Robustness Test

This section conducts a robustness analysis of the MGTWR model by replacing variables. On the basis that the influence of other driving factors remains unchanged, the influencing factor of technological innovation is replaced with the Fudan University China Urban and Industrial Innovation Index. The model fitting results (AIC = -1570.347, $R^2 = 0.9995$) are consistent with the original model, indicating that the empirical results of this study are robust.

9. Conclusions and Recommendations

9.1 Main Conclusions

Temporal Evolution: Urbanization levels rose steadily (2014-2023), with fast growth in Quzhou, Suqian, and Lishui.

Spatial Pattern: Eastern cities are highly urbanized (HH clusters), western cities low (LL clusters), with positive spatial autocorrelation strengthening over time.

Driving Factors: Investment in Science and Technology and industrial structure advancement benefit all cities; highway density and population density drive western regions; per capita GDP and openness boost central-southern and eastern regions, respectively.

9.2 Policy Recommendations

Balanced Regional Development: Core cities (Shanghai, Hangzhou) should transfer industries to western regions; underdeveloped cities (Huangshan, Chizhou) should improve infrastructure.

Strengthen Technological Innovation: Establish innovation funds and attract talent via relaxed policies.

Optimize Infrastructure: Expand road networks in western cities; reduce congestion in eastern cities.

Enhance Openness: Develop free trade zones in coastal cities; improve connectivity in inland cities.

Upgrade Industrial Structure: Promote high-tech industries and transform traditional manufacturing.

9.3 Limitations and Future Directions

This study employs Euclidean distance for spatial analysis. In the future, network distance can be incorporated to enhance the accuracy of the analysis. The study did not include emerging indicators such as digital urbanization, and the integration of 2023 data has not yet been fully completed, leaving room for improvement in the indicator system and data quality. In the future, further exploration can be conducted on the interactive relationship between urbanization and the ecological environment, and the ecological effects of urbanization development can be analyzed to provide references for the Yangtze River Delta region to achieve the coordinated development of urbanization and the ecological environment.

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