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Spatiotemporal Evolution Characteristics and Influencing Factors of the Pearl River Delta Urban Agglomeration

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Abstract

Pinpointing the driving forces and spatiotemporal variances in the evolution of urban agglomeration landscape patterns is key for enhancing territorial spatial development and attaining high quality regional growth.Taking Guangzhou and Shenzhen, the core cities of the Pearl River Delta, as cases, this study constructs a four-dimensional driving factor system. The system includes natural constraints, socioeconomic factors, infrastructure, and policy planning. Based on 2015-2023 panel data, the Geographically and Temporally Weighted Regression (GTWR) model is employed to analyze their spatiotemporal impacts. The results show that: (1) Topographic relief is the core natural constraint: Guangzhou has long been under high-intensity topographic constraints, while Shenzhen remains at an extremely low level. (2) Socioeconomic driving forces have strengthened overall but show structural differentiation: In the later period, Shenzhen's driving force outpaced Guangzhou's, with its export-oriented economy contributing significantly. GTWR uncovers notable spatiotemporal heterogeneity: Per capita GDP had an inverted U-shaped effect on Shenzhen, but a steadily strengthening one on Guangzhou. By 2023, natural constraints and policy guidance shaped Guangzhou's landscape evolution, while technological innovation and rail transit steered Shenzhen's. (4) The comprehensive effect evolved from socioeconomic dominance to infrastructure guidance and then to policy planning drive, reflecting the transformation from extensive expansion to intensive improvement. These findings provide a scientific basis for differentiated territorial spatial governance of urban agglomerations.

Keywords

Pearl River Delta Urban Agglomeration; GTWR; Box Diagram; Grey Correlation Analysis.

1. Introduction

Urban agglomerations have become core spatial carriers of global economic development and urbanization in the 21st century. As the core engine of the Guangdong-Hong Kong-Macao Greater Bay Area (GBA), the Pearl River Delta (PRD) urban agglomeration generated a regional GDP of 11.9 trillion yuan in 2025, with Guangzhou and Shenzhen contributing approximately 7 trillion yuan. While the PRD has formed a comprehensive transportation network, it faces challenges including regional development disparities, fragmented landscape structures, and administrative barriers. Systematically analyzing the spatiotemporal evolution [1] characteristics of population distribution and its driving mechanisms is critical for promoting high-quality regional development.

1.1. Literature Review and Research Gaps

1.1.1. Theoretical and Empirical Research on Population Spatial Distribution

International research on urban agglomerations has a long history and formed a complete theoretical system.[2] Early studies proposed the core-periphery theory, while recent research has expanded to the network attributes of population mobility. Domestic studies have confirmed that the PRD exhibits a typical "core agglomeration, peripheral diffusion" pattern, with an increasingly prominent "central location inhibition effect". However, most studies focus on static spatial patterns rather than long-term dynamic evolution.[3]

1.1.2. Research Progress on Influencing Factors of Population Distribution

Economic factors are generally recognized as the primary driving force for population mobility, followed by transportation infrastructure, government policies, and public services. In the PRD, economic development indicators are highly correlated with population changes. Nevertheless, existing studies have not systematically quantified the relative contribution of each indicator, nor explored the spatiotemporal heterogeneity of influencing factors across different cities and stages.

1.1.3. Application of Spatial Econometric Methods in Population Research

Spatial econometric models have evolved from ordinary least squares (OLS) to geographically weighted regression (GWR), geographically and temporally weighted regression (GTWR), and multi-scale geographically weighted regression (MGWR), which improves the accuracy of local spatial structure analysis.[4, 5, 6] However, most studies use a single model, and few combine grey relational analysis (GRA) with multi-scale geographically and temporally weighted regression (MGTWR)[7] to explore population distribution mechanisms.[8]

1.1.4. Research Gaps

Three main research gaps are identified:(1)Single-dimensional perspective focusing on static patterns or single factors;(2)Insufficient quantitative analysis of driving factors and their spatiotemporal heterogeneity;(3)Methodological limitations with lack of comparative analysis of GTWR, MGWR, and MGTWR, as well as integration with factor screening methods such as GRA.[9, 10]

1.2. Research Objectives and Significance

1.2.1. Research Objectives

This study aims to:(1)Screen core driving factors of population distribution using GRA based on 16 socioeconomic indicators;(2)Construct and compare GTWR, MGWR, and MGTWR models to explore the spatiotemporal heterogeneity of driving factors;(3)Propose targeted policy recommenda-tions for optimizing population spatial distribution in the PRD.

1.2.2. Research Significance

Theoretically, this study integrates GRA with three spatial econometric models to form a systematic research framework, enriching the methodological system of urban agglomeration evolution research. Practically, the findings provide a scientific basis for territorial spatial optimization, population policy formulation, and public service allocation in the PRD[11], and can be extended to other urban agglomerations in China.

2. Data and Variables

2.1. Data Sources

This study covers nine prefecture - level cities in the PRD, namely Guangzhou, Shenzhen, Foshan, Dongguan, Zhongshan, Zhuhai, Huizhou, Jiangmen and Zhaoqing, from 2008 to 2024. The dataset includes 16 core indicators across five dimensions: population statistics, economic

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development, investment and consumption, opening-up level, fiscal and financial conditions, and people's livelihood well-being. Raw data are preprocessed using the box plot method for outlier removal and Z-score standardization to eliminate dimensional differences.

2.2. Variable Selection

Existing studies confirm that urban agglomeration spatial evolution is driven by both natural and anthropogenic factors. With socioeconomic development, industrial structure optimization, infrastructure improvement, and policy guidance have become dominant factors shaping urban spatial expansion. We select the year-end permanent resident population as the dependent variable, which most directly reflects the population scale and spatial distribution characteristics of urban agglomerations.

For independent variables, we construct a multi-dimensional indicator system consisting of 16 variables from five aspects, fully considering the PRD's unique characteristics as an export-oriented economic region and China's core growth pole. The selection of each indicator is based on classical regional economics and spatial econometrics theories, as well as existing research achievements [12, 13, 14, 15, 16, 17, 18, 19].

2.3. Descriptive Statistics

This section shows descriptive stats of the explained variable (permanent resident population) and 16 explanatory ones. It includes each indicator's min, mean, max, and standard deviation. The results in Table 1 reflect all variables' overall distribution and inter - city differences in the PRD urban agglomeration from 2008 - 2024.

Table 1. Descriptive Statistics of Variables

Variable	Minimum	Mean	Maximum	Standard Deviation
Permanent Resident Population (10,000 persons)	251.85	661.81	1897.80	397.12
GDP (100 million yuan)	715.85	9652.83	36801.87	8547.11
Per Capita GDP (yuan)	18951	87529.35	205714	37710.56
Industrial Value Added above Designated Size (100 million yuan)	408.15	4251.79	15860.11	3082.44
Fixed Asset Investment (100 million yuan)	325.71	2671.90	10195.38	2194.75
Total Retail Sales of Consumer Goods (100 million yuan)	233.81	2674.50	11012.62	2547.34
Total Exports (100 million yuan)	21.44	3247.60	28117.47	5271.99
Actual Utilization of Foreign Capital (100 million yuan)	1.81	67.82	730.10	127.44
Local Public Fiscal Budget Revenue (100 million yuan)	55.92	871.34	4257.70	907.56
Deposits of Financial Institutions (100 million yuan)	728.75	21714.74	135778.02	25714.23
Loans of Financial Institutions (100 million yuan)	374.15	16271.92	94830.33	19427.89
Consumer Price Index (%)	66.00	101.99	105.90	1.72
Per Capita Disposable Income (yuan)	5872	36891.74	81123	18554.33
Number of Students in Regular Secondary Schools (10,000 persons)	12.16	31.79	75.02	14.12
Number of Students in Primary Schools (10,000 persons)	12.63	52.67	133.21	27.41
Number of Hospital Beds (10,000 beds)	0.59	2.67	12.09	2.14
Number of Health Technical Personnel (10,000 persons)	1.03	4.68	21.04	4.01

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Next, the specific definition, calculation method and connotation of each variable in the text will be explained, and the statistical caliber and selection basis of each index will be clarified, as shown in table 2.

Table 2. Variable Definitions and Explanations

Variable Name	Calculation Method	Indicator Explanation	
Permanent Resident Population	Permanent resident population at year-end	Population scale	Reference [13, 14, 15, 16, 17, 18, 19, 20]
GDP	Annual regional gross domestic product	Economic aggregate	
Per Capita GDP	Annual GDP / Permanent resident population	Per capita economic level	
Industrial Value Added above Designated Size	Annual industrial value added of enterprises above designated size	Industrial output level	
Fixed Asset Investment	Annual total fixed asset investment of the whole society	Construction investment intensity	
Total Retail Sales of Consumer Goods	Annual total retail sales of social consumer goods	Consumer market scale	
Total Exports	Annual total value of exported goods	Foreign trade export level	
Actual Utilization of Foreign Capital	Annual actual amount of foreign direct investment utilized	Foreign capital attraction level	
Local Public Fiscal Budget Revenue	Annual total local public fiscal budget revenue	Local government financial strength	
Deposits of Financial Institutions	Year-end balance of local and foreign currency deposits of financial institutions	Regional capital stock	
Loans of Financial Institutions	Year-end balance of local and foreign currency loans of financial institutions	Regional capital supply intensity	
Consumer Price Index	(Current period CPI / Base period CPI) × 100	Regional price level	
Per Capita Disposable Income	Annual total disposable income / Permanent resident population	Resident income level	
Number of Students in Regular Secondary Schools	Year-end total number of students in regular secondary schools	Secondary education resource supply	
Number of Students in Primary Schools	Year-end total number of students in primary schools	Primary education resource supply	
Number of Hospital Beds	Year-end total number of actual hospital beds in health institutions	Medical facility scale	
Number of Health Technical Personnel	Year-end total number of health technical personnel in health institutions	Medical human resource level	

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As shown in Table 1, there are significant inter-city differences in all indicators across the PRD urban agglomeration. For the core explained variable, the permanent resident population ranges from 2.5185 million to 18.978 million, with a standard deviation of 3.9712 million, reflecting the obvious spatial imbalance of population distribution between core cities and peripheral cities. For economic indicators, the standard deviations of GDP, total exports, and financial institution deposits all exceed 5000, further verifying the significant development gap between core cities (Guangzhou, Shenzhen) and peripheral cities (Zhaoqing, Jiangmen). This significant spatial heterogeneity of population and economic development provides an ideal research scenario for exploring the differential driving mechanisms of population spatial distribution in the PRD using spatial econometric models.

3. Analysis of Spatiotemporal Evolution Mechanism of the Pearl River Delta Urban Agglomeration

In this chapter, the Grey Relational Analysis (GRA) method is employed to quantitatively identify the core driving factors affecting the spatiotemporal distribution of the permanent resident population in the Pearl River Delta (PRD) urban agglomeration. GRA, suitable for analyzing variable correlations in systems with incomplete information, is well-matched to the complex socioeconomic characteristics of urban agglomeration evolution. Through calculating the grey relational degree between the permanent resident population and 16 socioeconomic indicators, the relative importance of different driving factors and their inter-city differences are revealed. This provides a scientific basis for variable selection in subsequent spatiotemporal econometric modeling.

3.1. Selection of Correlation Factors

The year-end permanent resident population of the nine PRD prefecture-level cities from 2008 to 2024 is selected as the reference sequence, which is also called the parent sequence, reflecting population spatial distribution characteristics.

For the comparison sequence, which is also known as the sub-sequence, a comprehensive indicator system is adopted. This system consists of 16 socioeconomic variables covering five dimensions: economic development, investment and consumption, opening-up level, fiscal and financial conditions, and people's livelihood well-being. The various driving forces of population agglomeration and migration in the PRD region are fully captured by this multi-dimensional system.

3.2. Calculation of Grey Relational Degree

Grey Relational Analysis measures the degree of correlation between sequences by comparing the geometric similarity of their development trends. The closer the geometric shapes of two sequences are, the higher their grey relational degree. The calculation process consists of six core steps: define reference and comparison sequences, perform dimensionless normalization, calculate difference sequence and extreme values, compute grey relational coefficients (resolution coefficient ε=0.5), obtain comprehensive grey relational degree as the average of coefficients, and rank results by relational degree.

Comprehensive grey relational degree formula:

$$r(x_o, x_i) = \frac{1}{n}\sum_{ki=1}^{n} r\left(x_o(k), x_i(k)\right);i = 0, 1, 2, \cdots, m \tag{1}$$

A higher relational degree indicates a stronger influence of the corresponding factor on permanent resident population distribution.

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3.3. Grey Relational Degree Analysis of Cities in the PRD

This study applies grey correlation analysis (GRA) to quantify the grey relational degree between the resident population of nine cities in the Pearl River Delta and 16 socio-economic indicators over the period 2008–2024. The key driving factors shaping population spatial distribution are identified according to correlation values. Given the distinct indicator correlation features among cities, we pre-sent the analytical results in a classified manner. Driving indicator structures are highly consistent across most cities in the region and therefore presented collectively. As Zhaoqing exhibits obvious heterogeneity in indicator rankings, its results are listed for separate comparison. This approach effectively illustrates the overall trends of the Pearl River Delta Urban Agglomeration and the unique attributes of local cities. Detailed findings are shown as follows.

Table 3. Grey Relational Degree of the Top Five Indicators: Eight Cities in the Pearl River Delta

Socio-economic Indicators	Dong guan	Zhong shan	Fo shan	Guang zhou	Hui zhou	Jiang men	Shen zhen	Zhu hai
Gross Domestic Product	0.984	0.996	0.985	0.961	0.979	0.976	0.956	0.988
Per Capita Gross Domestic Product	0.905	0.976	0.957	0.903	0.957	0.967	0.933	0.974
Industrial Value Added above Designated Size	0.899	0.976	0.947	0.898	0.954	0.967	0.913	0.975
Fixed Asset Investment	0.888	0.972	0.938	0.884	0.951	0.940	0.901	0.966
Total Retail Sales of Consumer Goods	0.884	0.966	0.929	0.885	0.948	0.925	0.892	0.962

According to the results in Table 3, the key driving factors of population change are highly consistent across eight cities in the Pearl River Delta, including Dongguan, Zhongshan, Foshan and Guangzhou. Regional GDP and per capita regional GDP rank the top two in terms of grey relational degree, with values staying above 0.90. These two indicators are the core drivers of regional population flow and spatial agglomeration. Meanwhile, the added value of industries above designated size, fixed-asset investment and total retail sales of consumer goods all rank within the top five. This proves that industrial development, infrastructure investment and consumption vitality are important supports for population agglomeration in most Pearl River Delta cities. Overall, the population spatial patterns of this urban agglomeration are mainly shaped by economic development levels.

Unlike the above cities, Zhaoqing lies on the periphery of the Pearl River Delta. It differs greatly in economic foundation, industrial structure and urban development orientation, leading to obvious heterogeneity in the core factors of population agglomeration. The grey relational degree results of its indicators are presented separately below.

Table 4. Grey Relational Degree of the Top Five Indicators: Zhaoqing

Gross Domestic Product	Fixed Asset Investment	Total Retail Sales of Consumer Goods	Total Exports	Per Capita Gross Domestic Product
0.962	0.922	0.921	0.917	0.912

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According to the calculation results in Table 4, the driving mechanism of population agglomeration in Zhaoqing differs markedly from that of core cities in the Pearl River Delta. The grey relational degree of fixed-asset investment in Zhaoqing ranks second, exceeding per capita GDP. It becomes the second most important driving factor, only after GDP. Exports, consumption and other market-oriented and export-oriented economic indicators also achieve high rankings.

This result indicates that population agglomeration in peripheral cities relies more on urban infrastructure investment and fundamental economic growth, rather than per capita economic benefits and high-end industrial strengths. It reveals the spatial differentiation of population driving mechanisms across the Pearl River Delta Urban Agglomeration, and provides reliable data support for the subsequent analysis of heterogeneous driving mechanisms and core factor selection.

Comprehensive Analysis of Grey Relational Results

The city-level grey relational analysis reveals three key findings:

(1)Economic factors are the dominant driving force across all cities.

GDP consistently ranks first in all nine cities with relational degrees above 0.95, followed by per capita GDP, industrial value added above designated size, fixed asset investment, and total retail sales of consumer goods. This confirms that employment opportunities and income levels are the primary considerations for population migration decisions.

(2)Significant inter-city heterogeneity exists

Core export-oriented cities (Shenzhen, Dongguan) show higher relational degrees for total exports and actual utilization of foreign capital; peripheral western cities (Zhaoqing, Jiangmen) have higher relational degrees for fixed asset investment, reflecting their reliance on infrastructure construction; emerging industrial cities (Huizhou, Zhongshan) show balanced contributions from economic and public service factors.

(3)Weaker but growing impacts are exerted by public service factors

Relational degrees between 0.7 and 0.85 are held by education and healthcare indicators. This indicates that while economic opportunities remain the primary attraction, the quality of public service is increasingly influencing long - term settlement intentions.

4. Model Construction and Solution

In this chapter, three advanced spatial econometric models are constructed and compared: Geographically and Temporally Weighted Regression (GTWR), Multi-Scale Geographically Weighted Regression (MGWR), and Multi-Scale Geographically and Temporally Weighted Regression (MGTWR). These models are employed to quantitatively analyze the spatiotemporal heterogeneity of the driving factors affecting the distribution of the permanent resident population in the PRD. By comparing the performance of the models, the optimal framework for revealing the internal driving mechanisms of urban agglomeration development is identified.

4.1. Overview of Spatial Econometric Models

Spatially stationary variable relationships are assumed by traditional global regression models, e.g., OLS. However, the spatial non - stationarity inherent in geographic processes cannot be captured by these models. GWR addresses this by allowing coefficients to vary across locations but ignores the temporal dimension of panel data. The temporal dimension is further integrated by GTWR to analyze both spatial and temporal variations. GTWR is improved by MGWR, which assigns independent optimal bandwidths to each variable to capture multi-scale spatial processes. The advantages of both GTWR and MGWR are combined by MGTWR, which assigns independent spatiotemporal bandwidths to each variable to simultaneously capture multi-scale spatial characteristics and temporal dynamics.

4.2. Core Model Formulations

The general mathematical expression of the MGTWR model (the most advanced framework) is:

$$Y_i = \beta_0(\mu_i, \upsilon_i, t_i) + \sum_k \beta_{b_{sk}b_{tk}}(\mu_i, \nu_i, t_i)X_{it} + \varepsilon_i$$
$$i = 1,2,\cdots,n, j = 1,2,\cdots,k \tag{2}$$

where (μ_i, ν_i, t_i) represents the spatiotemporal coordinates of the i-th sample point; $\beta_{b_{sk}b_{tk}}(\mu_i, \nu_i, t_i)$ is the regression coefficient of the k-th independent variable estimated using its specific optimal spatial bandwidth b_{sk} and temporal bandwidth b_{tk}; X_{it} is the observed value of the k-th independent variable; and ε_i is the random error term.

MGTWR uses an extended back-fitting algorithm to estimate variable-specific spatiotemporal bandwidths and regression coefficients iteratively. The optimal bandwidth is determined using the corrected Akaike Information Criterion (AICc) to balance model goodness-of-fit and parsimony.

4.3. Model Results and Comparison

All three models were applied to the PRD dataset, and GDP was selected as the representative driving factor for comparative analysis.The model performance comparison is presented in Table 5.

The results show that model performance improves progressively from GTWR to MGWR and then to MGTWR. The MGTWR model achieves an exceptionally high R^2 of 0.995, indicating it can almost perfectly reproduce both the local and global spatiotemporal distribution of population. This superior performance is attributed to its ability to capture complex multi-scale spatiotemporal interactions. Therefore, we select MGTWR as the optimal analytical framework.

Table 5. Model Performance Comparison

Model	Goodness-of-Fit (R^2)
GTWR	0.951
MGWR	0.981
MGTWR	0.995

The MGTWR results reveal the following key characteristics of driving factor effects:

GDP shows a negative correlation with population growth: Coefficients range from -0.1609 to -0.1595 in 2024, reflecting the decoupling of economic expansion and population increase in the PRD. Core cities (Guangzhou, Shenzhen) have transitioned from labor-intensive to technology-intensive development, reducing their demand for low-skilled labor.

Industrial growth has a universal positive effect: Industrial value added above designated size is the only factor that consistently promotes population agglomeration across all cities, confirming that manufacturing remains the core engine of employment absorption, especially in emerging industrial cities.

Driving factors present an "east strong, west weak" spatial pattern: Eastern coastal cities (Shenzhen, Dongguan) have much higher economic vitality and population attraction than

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western inland cities (Zhaoqing, Jiangmen), resulting in persistent regional development imbalance.

Significant temporal dynamics exist: Recent economic developments have a much stronger influence on current population distribution than historical factors, with temporal weights decaying rapidly (optimal temporal parameter τ=0.2).

5. Summary

In this study, three spatial econometric models (GTWR, MGWR, MGTWR) are employed to analyze the spatiotemporal evolution of the permanent resident population in the Pearl River Delta (PRD) from 2008 to 2024. The following core conclusions and targeted policy recommendations are drawn.

5.1. Core Model Conclusion

MGTWR is the optimal analytical framework: The Multi-Scale Geographically and Temporally Weighted Regression (MGTWR) model, with a goodness-of-fit (R^2) of 0.995, significantly outperforms GTWR and MGWR. The multi-scale spatiotemporal heterogeneity of driving factors is accurately captured by it, providing the most reliable basis for decision-making.

A negative correlation is shown between GDP and population growth: In the PRD, especially in core cities (Guangzhou, Shenzhen, Foshan, Dongguan), a clear decoupling is presented between economic expansion and population increase. This reflects the region's fundamental transformation from labor - intensive to technology-intensive development.

An "east strong, west weak" spatial pattern is presented by driving factors: The population attraction of eastern coastal cities (Shenzhen, Dongguan) is far stronger than that of western inland cities (Zhaoqing, Jiangmen), resulting in persistent regional development imbalance.

A universal positive effect is had by industrial growth: Industrial value added above designated size is the only factor that consistently promotes population agglomeration across all cities. It is confirmed that manufacturing remains the core engine of employment absorption.

5.2. Policy Recommendations

Differentiated industrial strategies should be implemented: High-tech and modern service industries should be focused on by core cities. A shift should be made from pursuing population quantity to improving talent quality. Industrial transfer should be undertaken by peripheral cities, and characteristic manufacturing should be developed to enhance their employment carrying capacity.

Regional development gaps should be narrowed: The construction of intercity transportation networks should be accelerated, and equalization of public services between eastern and western regions should be promoted. The orderly transfer of industries and population from core to peripheral areas should be guided to achieve balanced development.

The supporting role of manufacturing should be strengthened: The digital and intelligent transformation of traditional manufacturing should be promoted, the industrial chain layout should be optimized, and stable employment absorption capacity should be maintained to support sustainable population development.

Precise spatial governance should be adopted: The high - resolution analysis capabilities of the MGTWR model should be leveraged to formulate city - specific population and economic policies. One - size - fits - all governance approaches should be avoided.

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