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Study on Influencing Factors and Planning Strategies of Population Spatial Distribution in Urban Fringe Areas from the Perspective of Built Environment—The Case of Wuhan, China

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Abstract: Rationally relieving the population of urban centers in large cities, such as megacities and supercities, is one of the current goals of population development in China. The fringe area of a large city is a potential area to undertake the population of the central area. Studying the relationship between the population and the built environment in this area can help urban planners formulate targeted construction strategies to attract the population of the city center to move to the fringe areas. This paper takes the fringe areas of Wuhan in 2010 and 2020 as its specific research object and puts forward the "5D" index system of built environments that affects the spatial distribution of population based on population data and built environment data. The OLS model is used to screen the influencing factors. This paper analyzes the correlation between population and built environment using a multi-scale geographic weighted regression model as well. According to the results of the regression analysis combined with the development and construction of the fringe areas of remote urban areas in Wuhan over the past 20 years, some suggestions are put forward for the planning and construction of remote urban areas. The results show that the "5D" index system of the built environment covers the influencing factors of the spatial distribution of the population. MGWR reveals the correlation between the influencing factors and the spatial distribution of population in the marginal areas on the global scale and the local scale, respectively, which provides a clear direction for the development of planning and construction to improve the attractiveness of the non-central areas to the population.

Keywords: urban fringe areas; population change; built environment; multi-scale geographic weighted regression; Wuhan City

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1. Introduction

The depopulation of megacities and supercities is a worldwide problem [1] and one of the significant research topics in the fields of demography, sociology, management, and urban and rural planning. China's National Development and Reform Commission (NDRC) report on Key Tasks for New Urbanization and Urban–Rural Integration Development in 2022 states that it will promote the optimal development of megacities and supercities and that mega-super-cities with a high population density in the central city and a sustained inflow of people will have to implement functional relocation in an orderly manner. Both Beijing and Shanghai, China, have successively introduced their long-range 2035 urban development master plans to prepare for the depopulation of the city center [2]. Based on the experience of these megacities and supercities, the development of urban space around the main urban area and increasing the attractiveness of urban fringe areas to the population has become a breakthrough for megacities and supercities to de-populate the main urban area [3].

Urban fringe areas are the transition zones between the city center and the rural hinterland bordering the central city. The degree of construction needs to be improved, and there is good space for development. The cost of large-scale construction is low. It is an urban space around the main city and it has the advantage of accepting the population of the central city [4]. Academics have gathered some research results on how to develop urban space around the main city and how to promote industrial agglomeration [5], but few scholars have explored how to increase the population attractiveness of urban fringe areas. From the perspective of urban planning and construction, in order to enhance the attractiveness of non-central areas to the population, it is necessary to study the relationship between various urban construction activities and the number of people and to provide specific planning and construction suggestions regarding different construction statuses of non-central areas of the city so as to promote the attraction of more people to those areas.

There are many influencing factors that have been found in current research to enhance attractiveness to urban populations, such as the economy, crime, leisure and education, and the urban environment [6]. Among these, the urban environment is increasingly recognized as an important factor influencing population change, especially the built environment of the city, such as road transportation, schools, hospitals, and other elements of the built environment [7].

The built environment refers to the human-made environment formed by people's modification of the natural background of the city and generally refers to urban land use, transportation planning, and some of the functional layout of the city [8]. Dr. Robert Cervero of the University of California, Berkeley, proposed the "5D" method of describing elements of the urban built environment, including density, diversity, design, distance to transit, and destination accessibility [9], which is a theory that better covers the urban built environment and has been widely recognized by academics [10–12].

To study the interrelationship between various built environment elements and the spatial distribution of population in marginal areas, it is necessary to analyze the correlation between built environment elements and the spatial distribution of populations in different time dimensions, to screen out the correlation index elements that can promote population growth, and to visualize them in geospatial space so as to improve the planning of different areas and to guide the distribution of the population and changes to its number. Established studies have shown that multiscale geographically weighted regression (MGWR) is one of the most important tools for analyzing spatial correlations [13]. As an optimized model of geographically weighted regression (GWR), the MGWR model allows for different bandwidths for each of the study variables, which facilitates a better investigation of the spatial relationship between demographic changes and built environment factors [14–16].

In this paper, we take the urban fringe areas of Wuhan in 2010 and 2020 as specific research objects to explore the correlation between the built environment and the population size of the city and to propose specific planning recommendations for urban construction in different areas in the fringe areas. More specifically, we ask two key questions: (1) How did the built environment and resident population of Wuhan's urban fringe areas evolve from 2010 to 2020? (2) What is the relationship between the various built environment factors and population attractiveness? What are the factors that affect the population change? The answers to these questions provide data and model support for policy makers and planning staff in formulating targeted policies to attract the population, which is of practical significance for increasing the population attractiveness of the fringe areas and relieving the population of big cities; the results of this study also provide theoretical support for summarizing the pattern of change in the population of urban fringe areas.

The remainder of this study is organized as follows: Section 2 presents a literature review; Section 3 provides a description of the study area and the related data for this paper; Section 4 describes the edge zone delineation method, least squares method, and multiscale geographically weighted regression analysis methodology used in the study;

Section 5 analyzes the modeling results and provides recommendations for planning; and Section 6 concludes and discusses.

2. Literature Review

This paper describes the relevant literature in three areas: the factors influencing changes in population size, indicators of built environment elements, and applications of geographically weighted regressions.

Population change is affected by the social, economic, and urban environment, and the population itself, each of which involves different influencing factors that are extremely complex and will continue to change over time [17]. In this paper, by combing through the literature related to the factors influencing population change in recent years (Table 1), we found that [2,6,7,18–23]:

Table 1. Factors affecting demographic change.

Author	Year	Research Focus	Method	Conclusion
Ralph, H. [6]	1977	The study ranked 100 cities based on 80 indicators and gave equal weight to four categories: economy, population/environment, crime, and entertainment/education to measure city attractiveness.	City index rankings and multiple regression analysis	There is no significant relationship between the population size of the 100 cities and their comparative status in terms of economic, demographic/environmental, crime, and recreational/educational characteristics. Only two indicators were significantly correlated with population size. These were population density and carbon monoxide air pollution.
Cheng, L., Wang, X. [18]	2003	This paper establishes a comprehensive index system for evaluating the quality of living space in China's regional center cities and their satellite towns on the basis of Rich Boyer's nine-factor index system and carries out a comprehensive evaluation of the quality of living space in Xi'an's satellite towns.	Analytic hierarchy process	Factors that have a greater impact on the quality of urban living space and thus increase the attractiveness of the population, economic conditions, level of education, level of health, and transportation.
Zhang, W., et al. [7]	2005	The article selects service facilities, natural environment, traffic conditions, location conditions, and other elements to construct a model to evaluate the degree of location advantage of the residential environment in different areas of Beijing and analyze its spatial characteristics.	Multiple regression analysis and ArcGIS	Differences in the living environment directly affect the population's relocation behavior and decision making on residential location, and areas with a high degree of locational advantage in the living environment also have relatively high prices for commercial housing, and are also the preferred areas for the population to choose living space.
Wang, W. [19]	2005	The article uses principal component analysis and the spatial superposition method of GIS to quantitatively analyze and evaluate the spatial distribution of quality of life in Hangzhou city in townships and streets.	Principal component analysis and ArcGIS	Studies show that Hangzhou's population remains concentrated in city centers with higher quality of life and that economically developed or densely populated areas are more attractive to highly educated people and high-income families.
Gao, Z. [20]	2012	Based on the three dimensions of institutional environment, social and cultural atmosphere, and living environment, the article establishes an evaluation index system for the attractiveness of talents in Shanghai and analyzes in depth the various external factors affecting the attractiveness of talents in Shanghai.	Analytic hierarchy process	The results show that the "institutional environment" has the greatest impact on the attractiveness of Shanghai's population, followed by the "living environment", which has a slightly greater effect on the attractiveness of Shanghai's population than the "social and cultural atmosphere".
Wang, H., et al. [21]	2017	The article explores the characteristics of Shanghai residents' housing preferences by investigating the types and preferences of residents' housing choices and sorting out influencing factors, including facility configuration, location and transportation, housing conditions, price factors, natural and social environments, etc.	Stated preference method and discrete choice model	Shanghai's suburbs have been the fastest-growing areas in terms of population density in recent years due to lower housing prices and better transportation facilities in the suburbs, which make them more attractive places to live, but the center of the city is still attractive to the population due to the improvement of education and other infrastructures.

Table 1. *Cont.*

Author	Year	Research Focus	Method	Conclusion
Institute for Urban Strategies [22]	2018	The report focuses on a multi-dimensional evaluation and ranking of six primary indicators: economy, R&D, cultural exchange, livability, environment, and transportation.	City index rankings	In 2018, the top five cities in the overall ranking based on the six assessment indicators remained unchanged—London, New York, Tokyo, Paris, and Singapore—which could also reflect the strength of the cities' attractiveness to the population.
Jiang, B., et al. [23]	2018	To study the impact of three factors, namely, the total number of women of childbearing age, the age structure of women of childbearing age and fertility, and the number of births from the 1980s to 2010.	Cross-sectional analysis and longitudinal analysis	Changes in the number of births in the country are influenced by changes in the total number of women of childbearing age, the age structure of women of childbearing age, and the fertility rate, with different factors playing a major role at different times.
Pan, Q., et al. [2]	2021	The study comprehensively analyzes the intrinsic factors and mechanisms of population distribution in far-away urban areas, establishes a system of indicators for evaluating the attractiveness of the population in far-away urban areas, and identifies and extracts the salient elements of population attraction.	Multivariable regression, tobit model, and GWR	The rail station will attract people to move from far away to live near the station, and the increase in output accessibility and green space accessibility will also attract more people, while the increase in accessibility of elderly care facilities will reduce the attractiveness of the population.

A part of the research focuses on natural variations in population size, such as birth and death rates. Another part of the research explores ways to increase the attractiveness of the population from the aspects of economy, leisure and education, crime, and the urban environment. For example, Ralph H. Todd selected 80 indicators from four aspects: economy, environment, crime, leisure, and education to measure the population attractiveness of cities [6]. Japan selected 70 indicators from six aspects: economy, research and development (R&D), culture, housing, environment, and accessibility to assess the city competitiveness index [22]. Pan et al. [8] identified four factors of population attractiveness in distant urban areas in terms of public service facilities, transportation facilities, industry, and ecological environment. However, we can see that there are very few studies exploring the increase in population attractiveness from the perspective of urban built environments. Although the existing literature on population change has touched on the factors of the urban built environment, there is a lack of research results systematically analyzing the relationship between the built environment and the spatial distribution of the population in urban fringe areas. The urban built environment is the main material carrier of human life [8] from the perspective of urban planning, exploring the correlation between urban built environment factors and population change, and improving the built environment construction in the peripheral areas can provide reference suggestions to promote the population evacuation of the central city. At the same time, this paper tries to analyze the factors influencing population growth in urban fringe areas in a more systematic way from the perspective of planning and construction, which provides a novel perspective for the evacuation of large urban centers.

The built environment is mainly referred to as the urban built environment. Dr. Robert Cervero optimized Reid Ewing's "3D" elements of the built environment and proposed the "5D" elements of the built environment [8]. In the quantitative analysis of the built environment by scholars at home and abroad, the indicator system of "5D" elements is generally accepted as the main measurement basis. According to the authoritative analysis of Handy and other scholars, the urban built environment is a man-made environment that is set up in order to provide the space needed for normal human activities, including the spatial environment under the interaction of many factors, such as road transportation, land use, buildings, infrastructure, and so on [24]. In urban construction, the built environment encompasses location, public service facilities, retirement facilities, jobs, the ecological environment, transportation facilities, and policies [25]. The built environment can largely influence the level of urban population attraction, and a superior built environment will result in a high urban population attraction and vice versa [26]. It can be seen that from the perspective of urban planning, exploring the correlation between built environment factors and population change is a crucial and powerful supplement to provide data support for improving the built environment construction in urban fringe areas and promoting the population decanting of large urban centers.

Research on the application of the MGWR model has been applied to the study of housing prices [27–29], neighborhood vitality [13,30], and traditional villages [31]. Few scholars have used the MGWR model to study urban population issues. Li used the MGWR model to analyze the factors influencing the level of economic development in the Yangtze River Delta region from 2010 to 2018 and concluded that factors such as the employed population had a significant impact on the economic development of the Yangtze River Delta region, but they started from the perspective of the population as an influencing factor and did not use population as a focus point [32]. Some scholars have also used the MGWR model to study built environment issues and discuss the association between the built environment and the ventilation potential [33]. In the absence of academic research on the correlation between the built environment and population, the MGWR model can be used to explore the association between them based on the academic perspective of causality in regression modeling.

To sum up, this paper takes the Wuhan urban fringe area as the specific research object, based on the population data and built environment data of the Wuhan urban fringe area in 2010 and 2020, and takes the 5D elements of the built environment proposed by Robert Cervero as the main influencing factors for the spatial distribution of the population, and researches the evolution of the population and the built environment of the Wuhan urban fringe area, as well as the correlation between the two over the past 20 years, and then deciphers the relationship between the population and the built environment with the results of the MGWR model. Finally, it synthesizes the actual development and construction of Wuhan's urban fringe area, analyzes the interaction between the built environment and population, and summarizes the pattern of population change in the urban fringe area to improve the built environment construction in the urban fringe area, provide reference suggestions for increasing the attractiveness of the population in the fringe area, and promote the population dissolution of the central city.

3. Research Area and Data

3.1. Overview of the Research Area

The study area of this paper is Wuhan City, Hubei Province. Wuhan, located in the middle reaches of the Yangtze River, is an important city in central China and the capital city of Hubei Province. Wuhan, one of the seven central cities in mainland China, consists of 13 administrative zoning districts, including Caidian, Jiangxia, Huangpi, Xinzhou, East—West Lake, and Hannan districts, which are part of the distant urban areas, and Jiangan, Jianghan, Qiaokou, Hanyang, Wuchang, Qingshan, and Hongshan districts, which are part of the main urban areas, covering a total area of 8569.15 km^2 (Figure 1).

Wuhan experienced rapid urbanization between 2010 and 2020. From 2010 to 2020, the built-up area expanded from 500 km^2 to 885 km^2 [34], the urban resident population increased from 9.78 million to 12.32 million [35], and the urbanization rate increased to 84.56% [36].

3.2. Data Source

The data used for this paper include Wuhan administrative district data, Wuhan land use, population density, road network, employment, construction, public transportation, education, culture, medical care, sports, and commercial facilities POI data from 2010 to 2020, as shown in Table 2.

The original data used in this paper were compiled from the following sources. The land-use data were obtained from ZENODO (Zenodo is a well-known data-sharing platform, a one-stop publication of research results and funding information); population data were obtained from WorldPop (https://www.worldpop.org, accessed on

23 March 2023); Wuhan Road Network Data were obtained from OpenStreetMap (https://www.open-streetmap.org, accessed on 26 March 2023); architectural data were obtained from ImageMap self-mapping; public transportation, education, culture, medical, sports, and commercial POI data were obtained from Gaode Map (accessed on 26 March 2023) crawling. Considering the difficulty and completeness of data acquisition, a total of 2 periods of data from 2010 and 2020 were selected for the study, and all the above data were uniformly projected onto the WGS_1984 coordinate system in ArcGis 10.5. And a spatial database of the factors influencing the built environment of population change in the fringe areas of Wuhan was constructed based on this data.

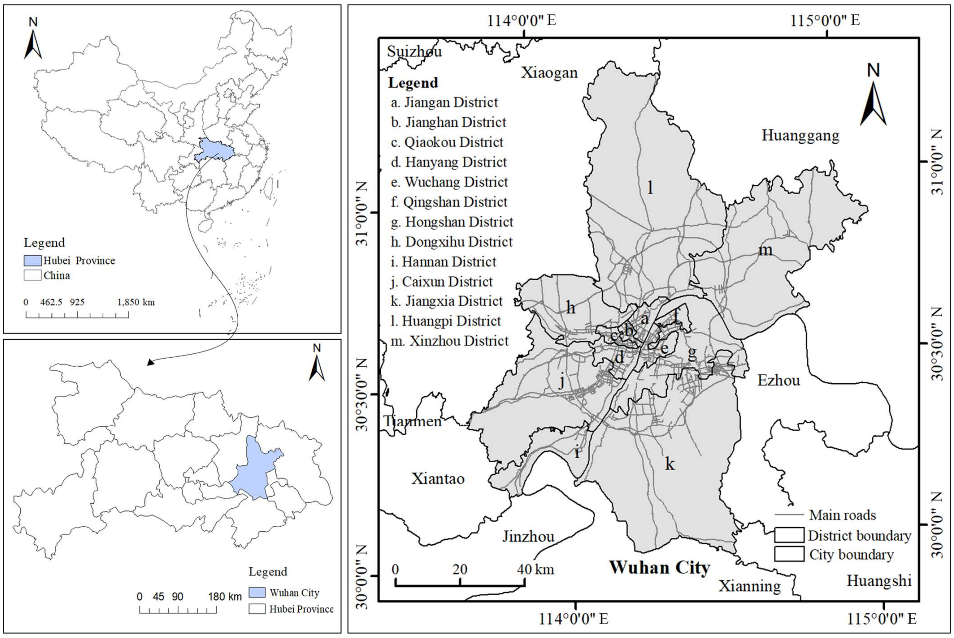


Figure 1. Research area.

Table 2. Data sources.

Type	Data	Data Sources	Processing
Wuhan city land-use data (2010–2020)	Wuhan 30 m resolution land-use data 2010–2020	ZENODO (https://zenodo.org, accessed on 2 April 2023)	ArcGis 10.5 extraction processing for each type of land
Population density	Spatial distribution of population data 2010–2020	WorldPop (https://www.worldpop.org, accessed on 23 March 2023)	ArcGis 10.5 raster extraction
Building outline	Building outline data in Wuhan from 2010 to 2020	Self-drawn image map	ArcGis 10.5 calculates building density
Wuhan city road network data	Wuhan City's urban trunk road network data from 2010 to 2020	OpenStreetMap (https://www.open-streetmap.org, accessed on 26 March 2023)	ArcGis 10.5 calculates coverage and accessibility
POI data	Spatial data points of public transportation, education, culture, medical care, sports, and commercial facilities in Wuhan from 2010 to 2020	Gao De Map crawl (https://www.amap.com, accessed on 26 March 2023)	ArcGis10.5

4. Methodology

4.1. Research Framework

The research idea of this paper was to first correlate the population data with the Wuhan urban fringe areas, analyze the spatial pattern of the population in 2010 and 2020, conduct spatial autocorrelation analysis of the population, and explore the clustering characteristics of the population. Second, we extracted the population influencing factors based on the "5Ds" of the built environment, conducted spatial autocorrelation analysis on the population influencing factors, obtained their clustering characteristics, and calculated the results of the indicators of the corresponding population kilometer grid. Then, the population influencing factors were pretreated using OLS (Ordinary Least Square for short) to screen variables, and the screened built-up environmental influencing factors were used as independent variables to construct the MGWR model with population. Finally, the degree of correlation between each influencing factor and population was analyzed, and planning suggestions to increase population attractiveness were put forward in combination with the development characteristics of each remote city. The specific technical process is shown in Figure 2.

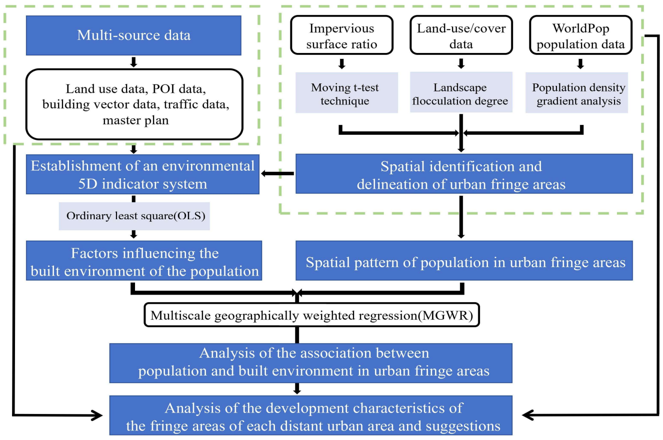


Figure 2. A framework for analyzing workflows.

4.2. Methodology for Determining the Extent of Urban Fringe Areas

We initially extracted the abrupt point of impervious surface and the degree of landscape flocculation from the urban fringe area for spatial superposition operation and directly identified the overlapping area where both of them were judged as urban fringe areas. Those with only one indicator were judged to be an urban fringe area; that is, they were referred to as a non-overlapping area, filtered using population density thresholds, and screened using population density thresholds. Those meeting the urban population density threshold were judged as urban fringe areas; otherwise, they were not judged as urban fringe areas. This method took into account the change in impervious areas, landscape disorder, and population density, and finally determined the scope of urban fringe areas [37].

(1) Impervious Surface Ratio and Sliding *t*-test Technique

The impervious surface ratio in the urban core is large and can reach up to 0.8–0.9 due to the construction of a large number of municipalities and buildings. In contrast, the impervious surface ratio in rural areas is very small, usually not higher than 0.2. As the urban fringe area is a combination of the urban core area and rural area, its impervious surface ratio often has sudden change points in space, and then we can initially identify the boundary of the urban fringe area by extracting the mutation points of the impervious area ratio.

(2) Landscape Flocculation Degree

Land use in the urban core is usually more regular and organized, whereas rural areas are mostly agricultural land and have a single type of land use, so the disorder of the landscape pattern in these areas is usually low. On the other hand, the urban fringe area is usually a transformation zone from a rural area to an urban core area, where some sites are developed and constructed, characterizing the built-up area. Some sites retain the characteristics of the rural areas before development and construction, where various types of land use are intertwined, the layout is loose, and the degree of landscape flocculation is high [38]. It follows that recognizing urban fringe areas can be based on urban–rural spatial differences in landscape flocculation.

(3) Population Density

As a phenomenon of human agglomeration, population density is a direct indicator of urban existence. On urban land, population density is higher in urban cores and lower in rural areas; urban fringe areas are the transition areas between the two, and the population density shows a gradient change pattern. Based on this pattern of change in population density, we can determine the extent of the urban fringe.

4.3. Models and Variables

4.3.1. Ordinary Least Square

OLS is the simplest of the linear regression models and is also known as the base model for linear regression. It can check the accuracy of the whole model and determine the run of each variable, whether there are unwanted variables, and whether there is autocorrelation in the data.

Linear regression is a type of regression model that is linear for parameter β (that is, the parameter is only in the form of a single square):

$$y_i = \beta_0 + \sum_{j=i}^{n} \beta_j x_{ij} + \varepsilon_i$$

In the formula, y_i is the value of the dependent variable in region i; x_{ij} is the value of the jth independent variable; ε_i is a random error term independently distributed throughout the regression model, which is usually assumed to obey N(0,σ2); the regression coefficient β_j is assumed to be a deterministic constant [39].

4.3.2. Multiscale Geographically Weighted Regression

The GWR model is a powerful tool for exploring the heterogeneity of spatial relationships. As a local spatial regression model, it generates a regression model describing the local relationships in each part of the study area; thus, the local spatial relations and spatial heterogeneity of variables can be well explained [40,41]:

$$y_i = \beta_0(u_i, v_i) + \sum_{k=1}^{m} \beta_k(u_i, v_i) x_{ik} + \varepsilon_i$$

In the formula, the value of the dependent variable at position i is y_i; the value of the independent variable at position i is x_{ik}(k = 1,2. . .m); (u_i, v_i) is the coordinate of the regression analysis point i; $\beta 0(u_i, v_i)$ is the intercept term; $\beta k(u_i, v_i)$(k = 1,2. . .m) is the coefficient of the regression analysis.

The weight function is calibrated using the adaptive method, using the BANDWIDTH_PARAMETER method to determine the bandwidth. The weighting function is as follows:

$$\omega_{ij} = \text{esp}\left[-\left(d_{ij}/b\right)\right]$$

b is the baseband width; d_{ij} is the distance from point (u_i, v_i) to point (u_i, v_i) [42].

MGWR is an optimization model for GWR. In GWR, each sample point is centered on a certain distance as a radius, the regression analysis is performed on the other sample points within the radius scale, and the "scale" is the bandwidth, which is the average value of the bandwidth of each dependent variable. In MGWR, on the other hand, each independent variable has its own bandwidth, and each dependent variable has a different sample point bandwidth model that can be regressed globally or locally depending on the different explanatory variables [27]. Compared to the traditional GWR, which can only select the same bandwidth for regression for all independent variables, MGWR uses the respective optimal bandwidth for each independent variable, which solves the problem of different variable scales and bandwidths. That is, smaller bandwidths are selected for regression for some independent variables because they exhibit strong variation characteristics locally, whereas larger bandwidths are selected for regression for some independent variables because they are more stable at the global scale.

The formula for the MGWR model is as follows:

$$y_i = \sum_{j=1}^{k} \beta_{bwj}(u_i, v_i)x_{ij} + \varepsilon_i$$

Here, bwj represents the bandwidth used for the regression coefficient of the jth variable.

Each regression coefficient β_{bwj} of MGWR is obtained based on a local regression with specificity of bandwidth, and this is the biggest difference from GWR, where β_{bwj} has the same bandwidth for all variables. MGWR's kernel functions and bandwidth selection criteria continue to use several of GWR's classic kernel functions and bandwidth selection criteria. In this article, we use the most commonly used Gaussian function and the AICc criterion [29].

4.3.3. Definitions of Variables

A built environment broadly refers to a man-made environment provided for human activities, including roads, infrastructure, housing, jobs, and other elements. Based on the "5D" evaluation indexes of the built environment and literature review, this paper constructs the index system of "demographic change influencing factors of built environment", which includes five categories and sub-indicators of density, diversity, design, distance to transit, and destination accessibility [8].

(1) Density

Density represents the intensity of crowd activity carried per unit area and generally includes population density, building density, and employment density, which are most commonly used in the built environment index system. Density is a reflection of urban economic and social and urban spatial structure, and numerous studies have shown that density is an important dimension of the built environment and that density greatly affects the spatial structure layout of the region as well as the movement trajectory of the inhabitants and other contents. In this paper, density is expressed as building density, whereas POI density is added to reflect the density of public facilities [43].

(2) Diversity

Diversity, also known as mixedness, generally includes both land-use diversity and POI diversity and can reflect whether land use or public facilities in a certain area can meet the needs of human life. Diversity is an important aspect of built environment assessment, reflecting the spatial function and spatial structure of a region. Most scholars believe that an increase in diversity within a certain region can enrich the architectural or land-use composition of the region and enhance regional vitality [44]. Ewing's research and review show that land-use mixing entropy is inversely related to motorized travel, with higher mixing entropy resulting in fewer motorized trips, and that high mixing can effectively increase transit and non-motorized travel, which is also an important indicator of population vitality [45]. In contrast, the lower diversity of the region, i.e., a single land-use type, does not meet the living requirements of the inhabitants. Diversity is specifically expressed in this paper as land-use mixing entropy and POI mixing entropy, reflecting the mixing of land use and infrastructure within the study area and the degree of regional functional compounding.

(3) Design

The design in this paper is mainly used to describe the road situation in the built environment, reflecting the efficiency, and the economy of the region. It is found that an increase in road network coverage and accessibility can increase the population density of the region to some extent, and there is an interrelated development pattern between transportation and population [46]. The design is specified in this paper in terms of road density, intersection density, and connectivity index.

(4) Distance to Transit

In this paper, public transportation refers to conventional bus and subway rail transportation. Areas with a higher level of public transportation service and a higher density of distribution of bus stops and subway stations have lower use of cars by residents and a higher proportion of commuting and walking using public transportation. Some studies have shown that a higher share of public transportation versus walking among residents' travel modes indicates that areas are more likely to develop population clusters. Higher accessibility for residents also tends to cluster more public services [47]. The specific expression of public transportation proximity in this paper is the closest distance of the grid to each station.

(5) Destination Accessibility

Residents' daily life destinations include various public service facilities, workplaces, city centers, green areas, and water systems. The better the public service facilities, the more prominent the convenience and happiness of the residents' lives. In public service facilities, this paper classifies seven aspects by POI as education, medical, sports, business, commercial, general hospital, and elderly facilities, as well as four aspects as district government, city center, green area, and water system; the three-level indexes are analyzed by grid reaching the nearest distance to each destination.

By combining these five aspects, 26 built environment evaluation indicators were constructed, as shown in Table 3.

Table 3. Index system of demographic influence factors.

Level Indicators	Secondary Indicators	Description
Density	Building density	Gross floor area/Fishing net area
	Density of educational facilities	Kernel density calculation formula: $p(x) = \frac{1}{N}\sum_{k=1}^{N}\frac{1}{h}K\left(\frac{x-x_k}{h}\right)$ Here, the parameter h is called the bandwidth, K(x) is called the kernel function, and K(x) satisfies the condition that $K(x) \geq 0, \int K(x)dx = 1$ $\int xK(x)dx = 0, \int x^2K(x)dx > 0$
	Density of medical facilities	
	Density of sports facilities	
	Enterprise density	
	Commercial density	
	General hospital density	
	Density of senior care facilities	
Diversity	Land-use mixing entropy	$H(X) = -\sum_{i=1}^{n} P_i log P_i$ denotes the entropy of the random variable X; is the probability that X takes Xi
	POI hybrid entropy	
Design	Road density	Total length of road/Total area
	Intersection density	Number of road intersections/Total area
	Connectivity index	Number of intersections/Total number of intersections
Distance to transit	Bus accessibility	Nearest distance of the fishing net to each target point in Arcgis
	Subway accessibility	
Destination accessibility	Accessibility of educational facilities	
	Accessibility of medical facilities	
	Accessibility of sports facilities	
	Commercial accessibility	
	Business accessibility	
	General hospital accessibility	
	Accessibility of senior care facilities	
	district government accessibility	
	Downtown accessibility	
	Green space accessibility	
	Accessibility of water systems	

5. Analysis of the Evolution of Population and Built Environment in Urban Fringe Areas of Wuhan City

5.1. Determining the Extent of the Urban Fringe Areas

In this study, the extent of candidate fringe zones extracted via impervious surface rate mutation points was spatially overlaid with the extent lines of candidate fringe zones extracted via landscape disorder degree. For the overlapping areas with the same conclusion, they were directly classified as urban fringe areas in Wuhan. For non-overlapping areas with different conclusions between the two, that is, where only one indicator is judged to be an urban fringe, a population density threshold is used for screening, with areas with a population density between 1000 and 3000 people/km^2 classified as an urban fringe, and the areas with population density not in this range not classified as urban fringe areas (Figure 3).

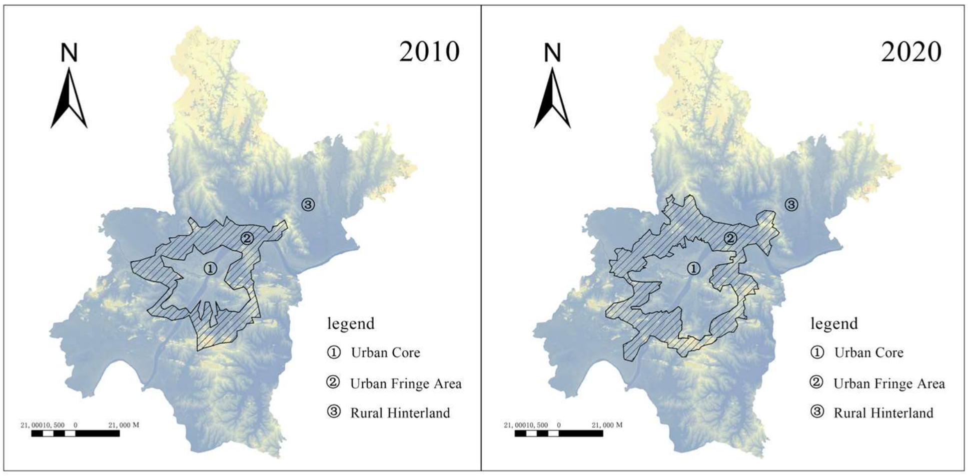


Figure 3. The extent of the urban fringe in Wuhan from 2010 to 2020.

5.2. Spatial Patterns of Population in Urban Fringe Areas

On the basis of the delimitation of urban fringe areas, this paper takes the urban fringe areas of Wuhan in 2010 and 2020 as the specific study objects and adds the part of the urban fringe areas converted to central urban areas in 2010 to the urban fringe areas in 2020 to facilitate comparison. From 2010 to 2020, Wuhan's urban fringe areas continued to expand to the periphery of the city, with area growth mainly occurring in Huangpi, East–West Lake, Caidian, and Hannan District.

The method of spatial analysis was applied in ArcGis, and the spatial distribution pattern of the population within the study area of Wuhan during the two periods of 2010 and 2020 was obtained. On the whole, there is a circular structure in the population distribution in Wuhan, which is shown as follows: highest in the central city, second highest in the urban fringe, and lowest in the rural hinterland. According to the analyzed data, in 2010, the fringe area had a total of 2,074,000 people, with a maximum of 32,100 people in each kilometer grid, located in Jiangxia District. In 2020, the fringe area had a total of 2,897,600 people, with a maximum of 36,200 people in each kilometer grid, still located in the same kilometer grid in Jiangxia District. According to Wuhan's administrative division of the urban fringe area, an area with a population of more than 5000 in 2010 was located in the East–West Lake District's Wujiashan Street, Evergreen Garden New District Street, Caidian District's Caidian Street, Houguan Lake Ecological Livable New City Management Committee, Xinzhou District's Yangluo Development Zone, Jiangxia District's Zhifang Street, Fuzuling Street, Hongshan District's East Lake Scenic Area Street, Guandong Street, Heping Street, Qingshan District's Wudong Street, Changqian Street, and Baiyu Mountain Street. In 2020, a population of more than 5000 areas in 2010, based on the expansion with the edge of the district, was added to the East and West Lake District of Jinghe Street, Caidian District of Zhashan Street, Hannan District of Shamao Street, Huangpi District of the Pan Longcheng Economic Development Zone, Jiangxia District of Zhengdian Street, and Hanyang District of the Hanyang District had also been turned into the central city of the Yongfeng Street Office. Comparing the population data of the two periods, it was found that the average population number in the grid of Wuhan fringe districts from 2010 to 2020 changed less and showed a more moderate overall growth trend. At the same time, it can be observed that the populations of East–West Lake District, Qingshan District, and Hongshan District continued to grow and were more stable; the populations of Papyrus Street in Jiangxia District and Yangluo Development Zone in Xinzhou District grew more; the populations of some areas in Caidian District, Huangpi District, and Hannan District grew more, but some areas grew slowly and the population changes were less (Figures 4 and 5).

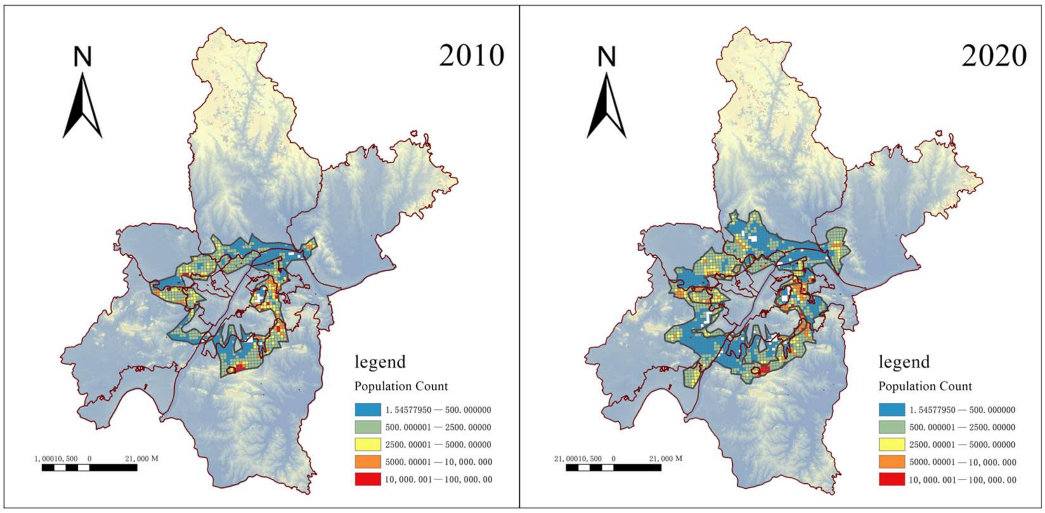


Figure 4. Spatial distribution of population in Wuhan's urban fringe in 2010 and 2020.

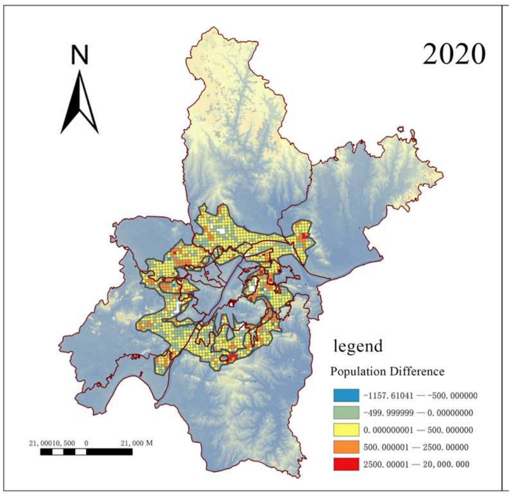


Figure 5. Population difference in urban fringe areas of Wuhan City in 2020.

5.3. Results and Analysis

5.3.1. Variable Screening

According to the results of the spatial autocorrelation analysis of population influencing factors, although built environment indicators as population influencing factors have strong spatial autocorrelation, the existence of multicollinearity among each of them cannot be excluded. In order to avoid the bias in estimation results brought about by the interaction between factors, it was necessary to test each factor and select the optimal factor as a variable to construct the regression model.

The OLS model was used in this study as an antecedent step to the GWR and MGWR models for further screening of explanatory variables by importing the full set of potential variables into the OLS. As shown in the table, it was used to screen for variables suitable for GWR among these explanatory variables affecting the population, usually based on the exclusion of redundant variables (variables with variance inflation factor values greater than 7.5) and statistical significance tests (probability b value less than 0.01).

The results show that, in 2010, the VIF values of educational facility density, medical facility density, commercial density, and general hospital density were higher than 7.5, indicating that these variables have multicollinearity problems and need to be eliminated. The b-values of commercial density, land-use mixing entropy, connectivity index, bus accessibility, subway accessibility, accessibility of educational facilities, accessibility of medical facilities, commercial accessibility, accessibility of general hospitals, accessibility of district governments, and accessibility of city centers were all greater than 0.01, indicating that these 11 factors had no significant effect on the population and needed to be deleted. In 2020, a VIF value higher than 7.5 for commercial density indicates that the variable had a multicollinearity problem and needed to be removed. The b-values of building density, density of medical facilities, land-use mixing entropy, intersection density, bus accessibility, accessibility of educational facilities, accessibility of medical facilities, accessibility of sports facilities, business accessibility, commercial accessibility, and general hospital accessibility were all greater than 0.01, indicating that these 11 factors had no significant effect on the population and need to be deleted. The remaining influencing factors were finally selected as explanatory variables for model construction via variable screening (Tables 4 and 5).

Table 4. Statistics of covariance test results for OLS variables in 2010 and 2020.

Variables	2010		2020	
	Probability b Value	**VIF**	**Probability b Value**	**VIF**
Building density	0.004910 *	1.505884	0.189267	1.690295
Density of educational facilities	0.000067 *	10.617651	0.000000 *	4.680789
Density of medical facilities	0.000000 *	16.408955	0.572632	7.352393
Density of sports facilities	0.000506 *	5.323807	0.000000 *	6.219783
Enterprise density	0.000000 *	3.954631	0.000000 *	3.117108
Commercial density	0.964749	16.595558	0.000000 *	9.347400
General hospital density	0.000152 *	20.707629	0.006496 *	5.858377
Density of senior care facilities	/	/	0.000070 *	2.758703
Land-use mixing entropy	0.383541	1.166208	0.635061	1.216620
POI hybrid entropy	0.000407 *	2.219505	0.000609 *	2.569134
Road density	0.000000 *	3.657860	0.000041 *	3.101853
Intersection density	0.000060 *	3.055031	0.192695	2.455613
Connectivity index	0.051274	1.493273	0.036192 *	1.427666
Bus accessibility	0.495531	1.780257	0.745722	2.168778
Subway accessibility	0.943849	4.750124	0.000277 *	1.532960
Accessibility of educational facilities	0.484203	2.331063	0.806583	2.447215
Accessibility of medical facilities	0.086862	5.315409	0.258241	2.863755
Accessibility of sports facilities	0.046233 *	2.398171	0.890450	1.770127
Commercial accessibility	0.444364	2.078590	0.589879	2.307591
Business accessibility	0.049031 *	3.256475	0.118101	2.713525
General hospital accessibility	0.620522	5.723466	0.240368	2.246450
Accessibility of senior care facilities	/	/	0.019892 *	2.183149
district government accessibility	0.104757	1.912072	0.019576 *	1.416074
Downtown accessibility	0.638305	5.522711	0.007627 *	1.899964
Green space accessibility	/	/	0.792585	1.916604
Accessibility of water systems	/	/	0.000035 *	1.439254

* Indicates that the data are statistically significant; / indicates that provisional data are missing

Table 5. Explanatory variables after screening in 2010 and 2020.

2010	2020
Density of sports facilities	Density of educational facilities
	Density of sports facilities
Enterprise density	Enterprise density
	Commercial density
POI hybrid entropy	General hospital density
	Density of senior care facilities
Road density	POI hybrid entropy
	Road density
Accessibility of sports facilities	Connectivity index
Business accessibility	Subway accessibility
Building density	Accessibility of senior care facilities
	District government accessibility
Intersection density	Downtown accessibility
	Accessibility of water systems

5.3.2. Model Results and Scale Analysis

As can be seen from Table 6, the goodness-of-fit R^2 of MGWR is higher than that of OLS, the value of AICc is lower than that of OLS, and the sum of squares of the residuals is smaller, which indicates that the above factors and the MGWR model can better explain the population distribution of Wuhan's urban fringe.

Table 6. Model calculation of key indicators.

Model indicators	MGWR	OLS	MGWR	OLS
Year	**2010**	**2010**	**2020**	**2020**
Adjusted R^2	0.706	0.232	0.725	0.301
AICc	1533.545	20,163.348	3024.997	31,542.716
Residual Sum of Squares	186.503	/	391.929	/

As can be seen from Table 7, in the MGWR regression results, the regression coefficients of 13 variables, including educational facility density, sports facility density, enterprise density, commercial density, comprehensive hospital density, old-age facility density, POI mixing entropy, road density, connectivity index, subway station accessibility, district government accessibility, downtown accessibility, and water system accessibility, are significant as a whole, among which the regression coefficients of five variables, namely, sports facility density, downtown accessibility, connectivity index, commercial density, and comprehensive hospital density, are significant. However, the regression coefficient of the single variable of the accessibility of old-age facilities is not significant, so it will not be interpreted subsequently.

In 2020, for example, the bandwidth of business density and district government accessibility was very small, i.e., 43, accounting for 2.5% of the total sample, which suggests that the spatial heterogeneity that existed between the two was large, and the population was affected differently in different regions. The bandwidths of downtown accessibility, sports facility density, general hospital density, and connectivity index were 1711 or 1712, which are global scales. There was no spatial heterogeneity, and the population was influenced by the variables in different regions in the same way. Among them, the smaller the bandwidth of the variables, the smaller the scale of spatial influence and the stronger the spatial heterogeneity, and vice versa [30].

Table 7. GWR and MGWR model bandwidths.

Variables	2010 GWR Bandwidth	2010 MGWR Bandwidth	2020 GWR Bandwidth	2020 MGWR Bandwidth
Constant term	60	84	156	641
Density of educational facilities	-	-	156	215
Density of sports facilities	60	48	156	1712
Enterprise density	60	147	156	43
Business density	-	-	156	86
General hospital density	-	-	156	1712
Density of senior care facilities	-	-	156	118
POI hybrid entropy	60	800	156	364
Road density	60	60	156	91
Connectivity index	-	-	156	1712
Subway accessibility	-	-	156	352
Accessibility of senior care facilities	-	-	156	1712
District government accessibility	-	-	156	43
Downtown accessibility	-	-	156	1711
Accessibility of water systems	-	-	156	45
Accessibility of sports facilities	60	44	-	-
Business accessibility	60	52	-	-
Building density	60	44	-	-
Intersection density	60	776	-	-

5.4. Interpretation of Results and Planning Recommendations

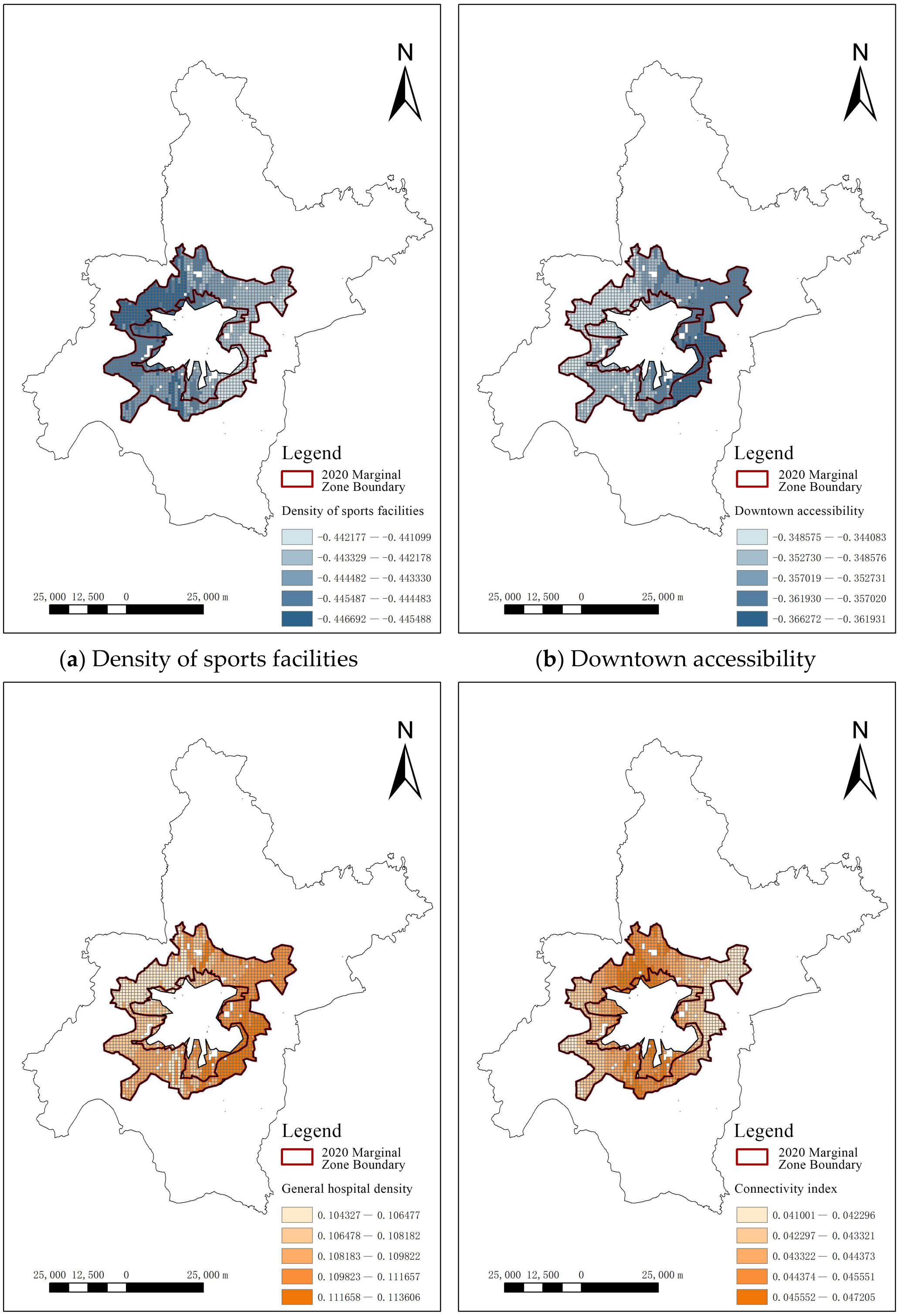
5.4.1. Global Impact Factors Built Environment and Population Linkage Analysis

Overall, the density of sports facilities shows a strong negative correlation with population size globally, with the strength of the effect decreasing spatially from northwest to southeast, as shown in Figure 6a, but the overall variability is not large enough to be on a global scale. As Wuhan has undertaken the 2019 World Military Games, many new stadiums have been built in recent years. However, the stadiums cover a large area, and it is difficult to find suitable sites in the central city, so most of the new stadiums are located in marginal areas where the population is sparse and the demolition and relocation difficulties are not too great, resulting in a negative correlation between the density of the stadiums and the population in the marginal areas. The impact of sports facilities on the population needs to be observed over a longer time cycle.

As shown in Figure 6b, city center accessibility has a strong negative correlation with population, and the intensity of the influence shows a weak spatial increase from northwest to southeast on a global scale. This shows that Wuhan is a polycentric city, and the influence of a single city center on the population is not very significant. Combined with the analysis of district government accessibility, the influence of district governments is more obvious for the fringe districts and the districts in distant urban areas.

General hospital density is weakly and positively correlated with population size globally, as shown in Figure 6c, while the strength of the effect is weakly and spatially decreasing from southeast to northwest, but with little overall variability on a global scale. The current situation of hospitals in Wuhan presents a circular distribution, and the distribution density is slightly higher in the east than in the west. In future development, the western fringe area should strengthen the construction of comprehensive medical facilities to promote attractiveness to the population.

As shown in Figure 6d, the impact of the connectivity index on the population is not very variable globally. Overall, the connectivity index shows a weak positive correlation with population density globally, and the strength of the impact is spatially weakly decreasing from the center of the country to the east and west, but the overall variability and coefficient values are small. The results of this analysis are consistent with the fact that areas with good transportation networks are usually more attractive to the population. Wuhan has a large number of lakes and small mountains, and this analysis reminds planners that the road network should be built to harmonize with the landscape and at the same time ensure easy accessibility.



(**a**) Density of sports facilities (**b**) Downtown accessibility

(**c**) General hospital density (**d**) Connectivity index

Figure 6. Coefficient plots of global-scale impact factors with population size in marginalized areas as the dependent variable in 2020.

5.4.2. Global Impact Factors Built Environment and Population Linkage Analysis

(1) Huangpi District

As shown in Figure 7, in 2010, the population of Huangpi District was mainly distributed in the Panlongcheng Economic Development Zone, Wuhu Street, and Name Street, mainly concentrated around the Songjiagang-Jurong Avenue-Panlongcheng subway line in the Panlongcheng Economic Development Zone, with a grid population of no more than 5000 people. This area is close to Wuhan Tianhe International Airport with the airport expressway, and there are Tangrenhai Lake and Panlong Lake located inside the area, which is adjacent to Houhu to the north. At the same time, in 2010, Huangpi District also had a population gathering near the name street office and the Qinglong-GaoChe-Wuhu subway line, but the overall population was small, with most grids having no more than 5000 people and 16% no more than 2500 people.

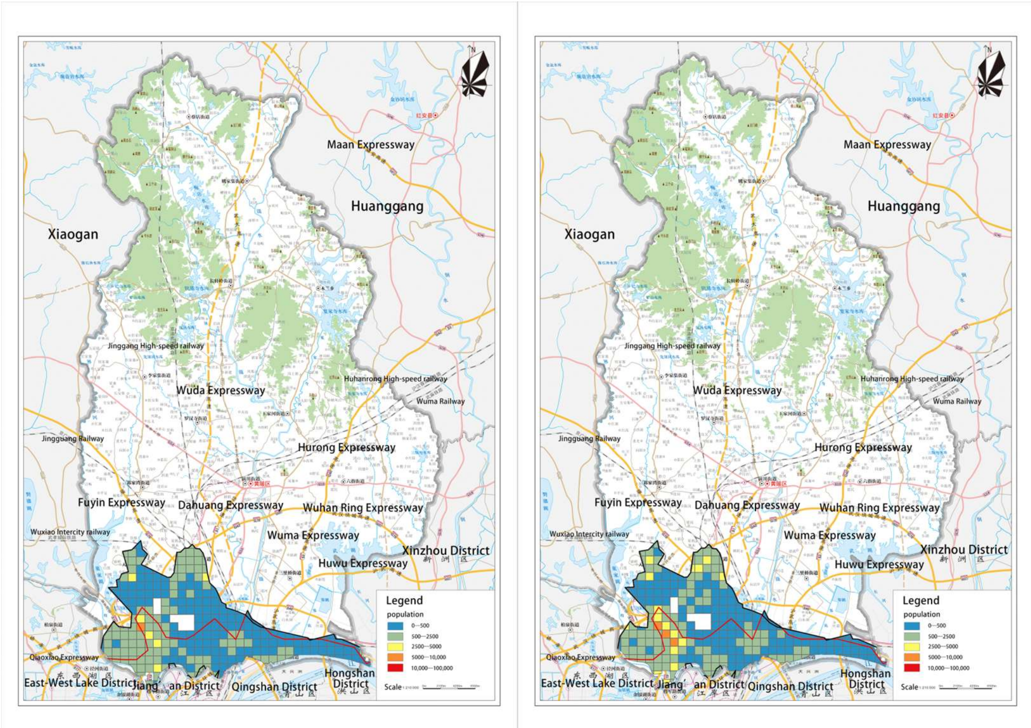


Figure 7. Evolution of the spatial pattern of population in Huangpi District in 2010 (**left**) and 2020 (**right**).

In 2020, on the basis of 2010, the edge area of Huangpi District extended to the north to Tianhe Street and Hengdian Street and showed a trend of gradually forming new population gathering points out of Tianhe Street and Hengdian Street Office. The population gathering point of Tianhe Street was close to Tianhe Airport and its subway station, with Airport North Road passing through. The population gathering point of Hengdian Street was located in the triangle area enclosed by Hanxiao Expressway S2, Daihuang Expressway S1, and Bypass Expressway G42, with G318 National Highway and railway line passing through internally. These two population centers had a grid size of more than 2500, whereas the remaining new development areas still did not exceed 500. In addition, the population of the Pan Long Cheng Economic Development Zone was growing steadily and the number of people around the subway line was more than 5000, whereas the population around the name of the street office was growing slowly and the population development was constrained.

Due to the distance of Huangpi District from the central area of Wuhan and the low degree of development, the area of the fringe area within the Huangpi District from 2010 to 2020 was relatively small, and the fringe area only accounted for 1/10 of the area of Huangpi District by 2020. From 2010 to 2020, observing the historical images of the two phases, it can be seen that the development of the fringe area shows a trend of circling from the main urban area to the north.

The MGWR results are shown in Figure 8. Among all the non-global scale population size-influencing factors, district government accessibility and business density have the greatest influence. Huangpi district government is located in the north of this fringe area, which is closer to the central city of Wuhan than the district government, and compared to the district government, this area is more obviously influenced by the central city of Wuhan, so a negative correlation between population size and the district government's accessibility occurs. Commercial density in the fringe areas of Huangpi District shows a clear positive correlation with population, with a strong positive correlation in the Panlongcheng Economic Development Zone and Shekou Street, and the area is distributed along the main roads of the city, suggesting that street-level commercials in the area promote the concentration of population. POI mixing entropy shows a negative correlation in Wuhu Street, and other regions show a weak positive correlation. The correlation coefficient in the population agglomeration area of the Panlongcheng Economic Development Zone suggests that the agglomeration of the population is related to the completeness of the region's public service facilities, and the higher the POI mixing entropy, the more the population. Road density and population size show a positive correlation in the region, and this correlation is stronger in the regions with higher road density. Subway accessibility is negatively correlated with the population in the western part of the Panlongcheng Economic Development Zone and the eastern part of Wuhu Street, and weakly positively correlated in other areas, with a stronger correlation in the northern part of the region, suggesting that population aggregation in the outer edges of the fringe areas, Hengdian Street and Tianhe Street, is more affected by subway accessibility, while the correlation in the Panlongcheng Economic Development Zone, which borders on the center of the urban area, is weaker. The density of educational facilities and commercial density show roughly the same trend in the region, but the correlation is not as strong as that of enterprise density. Business density and population size show a weak positive correlation in Wuhu Street and Panlongcheng Economic Development Zone and most of the western part of Tianhe Street, and a negative correlation in all the other areas of the fringe area of Huangpi District, with a significant negative correlation around the Daihuang Expressway in Shekou Street and the administrative committee of the Hankou North Trade and Logistics Hub, which is probably related to the fact that this area is the main trade and commerce concentration in Wuhan City. Water system accessibility and population size show a strong positive correlation near Houhu Lake and Hanbei River. The density of senior care facilities and the number of people show a weak negative correlation in Tianhe Street and the western part of the Panlongcheng Economic Development Zone and a strong positive correlation in Shekou Street and the Hankou North Trade and Logistics Hub District Administrative Committee.

Figure 9 shows the 2010 and 2020 Google Earth historical imagery of the urban fringe area of the Huangpi District. The blue dashed area on the map represents non-built-up land in 2010, and in 2020, a large number of houses and roads were built. These parcels include Tianhe International Airport, the area around Panlongcheng, Hengdian Street, and Wuhu. The development of the area is part of the new district construction in the last decade, with a greater emphasis on transportation links, which is generally consistent with the MGWR results. According to the MGWR regression results and the actual satellite image change map, building more commercial facilities in the Panlongcheng Economic Development Zone and Shekou Street and improving the level of commercial services can bring more population to the region. At the same time, in Huangpi District, the development of urban fringe areas and the degree of accessibility of the region related to the high degree of accessibility can increase the attractiveness of the population by improving the degree of accessibility of regional transportation and the construction of the subway in Hengdian Street and Tianhe Street; in the construction of ancillary facilities, it is recommended that priority be given to improving the coverage of education, the Panlongcheng Economic Development Zone, the name of the street to build additional educational facilities, and gradually improve the other ancillary facilities. In the western part, the streets in Tianhe Street and the streets of Wuhu can be considered the construction of the industrial park and promote its transformation and development.

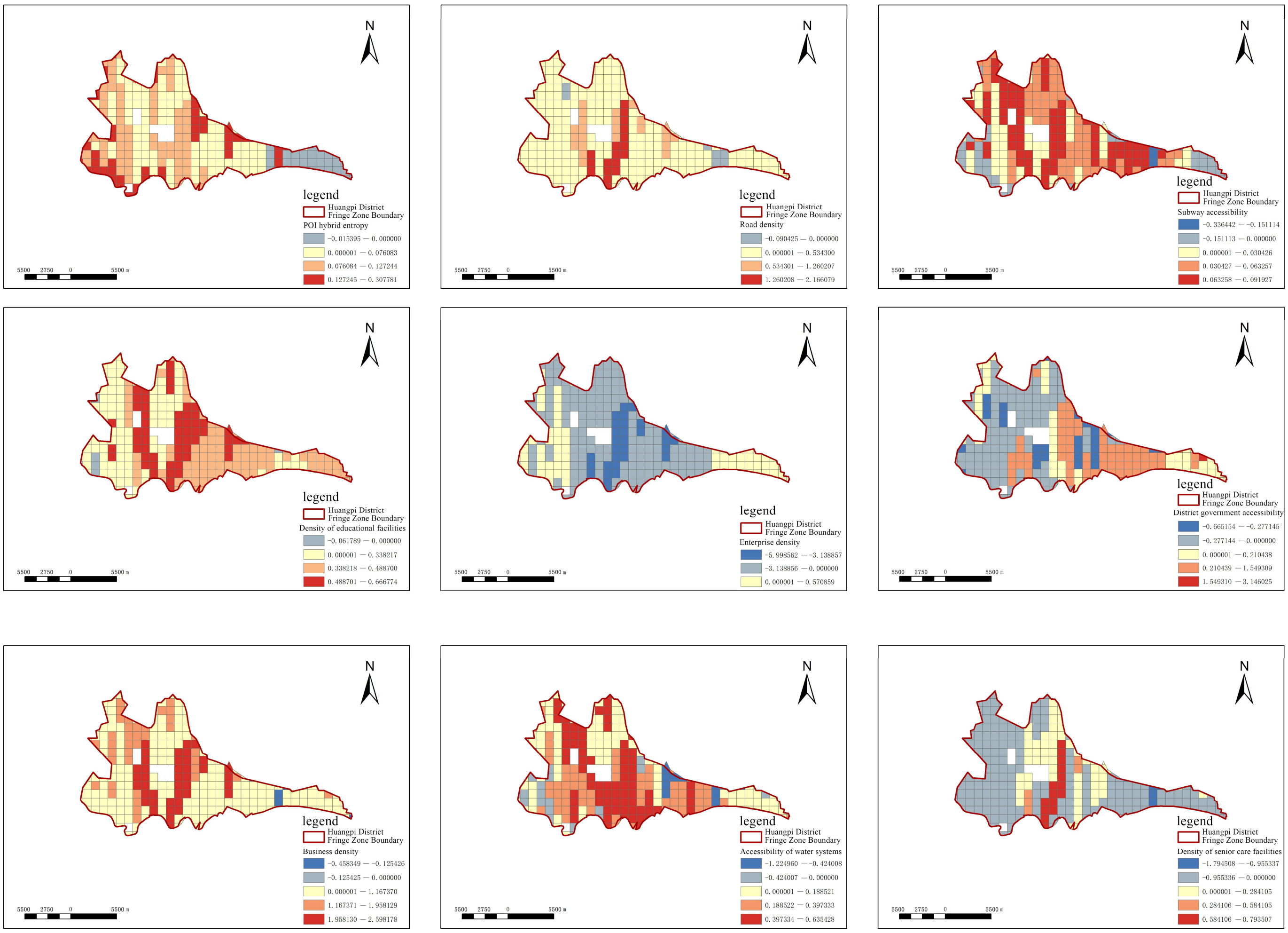


Figure 8. Coefficient plot of MGWR analysis with 2020 population size as the dependent variable for Huangpi District.

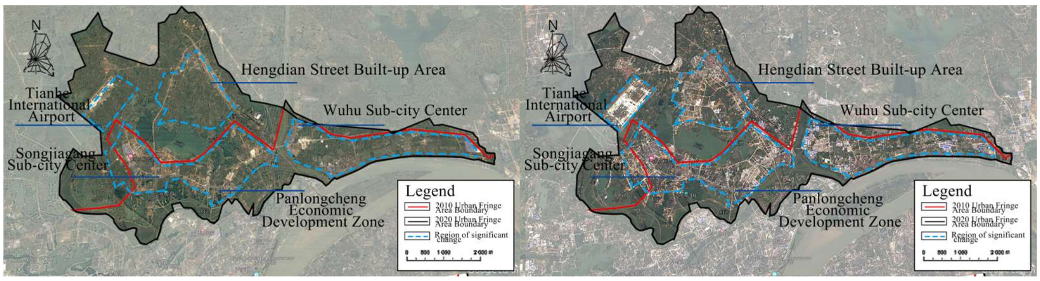


Figure 9. Google Earth historical images of Huangpi District urban fringe area in 2010 (**left**) and 2020 (**right**).

(2) East–West Lake District

According to the process of population spatial pattern evolution in the East–West Lake District from 2010 to 2020 (Figure 10), it can be seen that the population gathering in the fringe areas of the East–West Lake District during this time period mainly occurs in Wujiashan Street, Jinghe Street, Jinyinhu Street, and Evergreen Garden New District Street, with an average grid population of above 500. Among these, the population growth in Wujiashan Street is the most prominent, with an average grid population of over 5000 people. This area is located between the third and fourth ring roads in Wuhan, close to the Lingang Economic and Technological Development Zone, with Metro Line 2 passing through, and the population attraction is even stronger. While Cihui Street, Changqing Street, Bonded Logistics Management Office, Industrial Management Office, and Cross-Strait Science and Technology Industry Management Office have smaller populations, the grid population is barely more than 500 people. Most of this area is located outside the fourth ring road, the interior of the Wuhan City bypass highway and the Beijing-Guangzhou railroad line, where the population is less attractive.

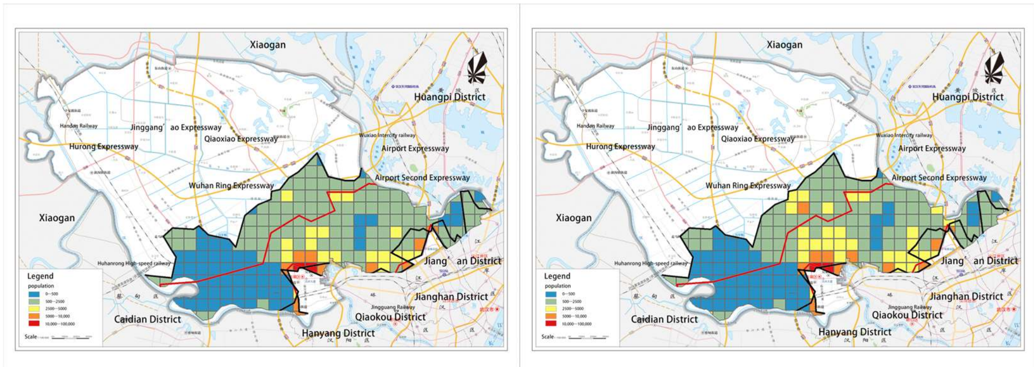


Figure 10. Evolution of the spatial pattern of population in the East–West Lake District in 2010 (**left**) and 2020 (**right**).

As shown in Figure 11, the street-built environment in the southwest direction of the East–West Lake District has changed more obviously, with a great increase in road density, enterprise density, and commercial density; the area is still mainly factory building construction, and the increase in enterprises can bring a large number of employment opportunities. Trail River Street, Jinyinhu Street, and Wujiashan Street are mainly focused on residential functions, and the built environment is dominated by the supporting construction of public service facilities. However, a higher density of enterprises is still an advantage for the development of the region, and industrial parks have developed rapidly during this decade, with the rapid development of the logistics industry. The old urban area of Wujiashan continues to develop, and in the future, it will develop into the center of the sub-city of Wujiashan.

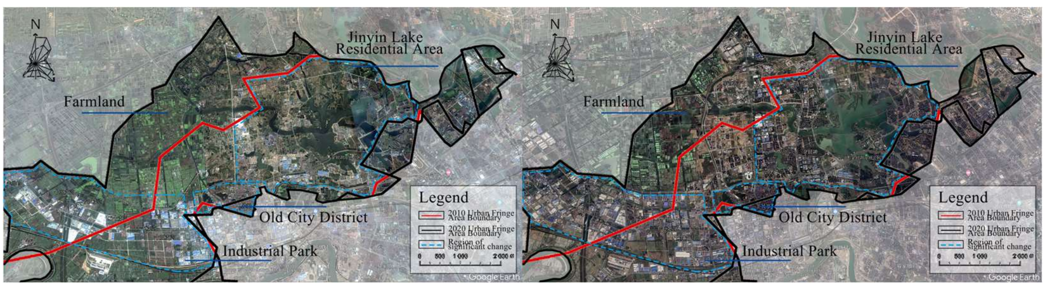


Figure 11. Google Earth historical images of the East–West Lake urban fringe area in 2010 (**left**) and 2020 (**right**).

The results of MGWR are shown in Figure 12, where POI mixing entropy, education density, and commercial density are positively correlated with the regional population, in which POI mixing entropy and education density show a weak positive correlation across the region, and POI mixing entropy is stronger in more densely populated areas, indicating that the completeness of public service facilities in the region affects the aggregation of the population. The positive correlation of education density is gradually stronger from the west to the east, and a stronger correlation is shown in the streets of Shuangguan Road. Commercial density exhibits a localized strong positive correlation with Wujiashan Street, Changqing Street, Cross-Strait Science and Technology Industry Administration, and Cihui Street showing strong positive correlations. Accessibility to the district government and the density of elderly care facilities are strongly negatively correlated with the population in Trail River Street, Jingyinhu Street, and Wujiashan Street, weakly positively correlated in the western part of the East–West Lake fringe area, and weakly negatively correlated in all other areas, suggesting that the closer to the district government, the more densely populated the area is to Wujiashan Street, and that these areas also rely on the support of the elderly care facilities. Subway accessibility and population size show a weak negative correlation in the densely populated street area, which is related to the fact that there are fewer subway stations in the area. Road density and population size show a weak negative correlation in Changqing Street, Cihui Street, and the Cross-Strait Science and Technology Industry Administration, a strong positive correlation in Jiangjun Road Street, and a weak positive correlation in other areas. Water system accessibility and population size show a strong positive correlation in the Treasure Lake and Trail River neighborhoods.

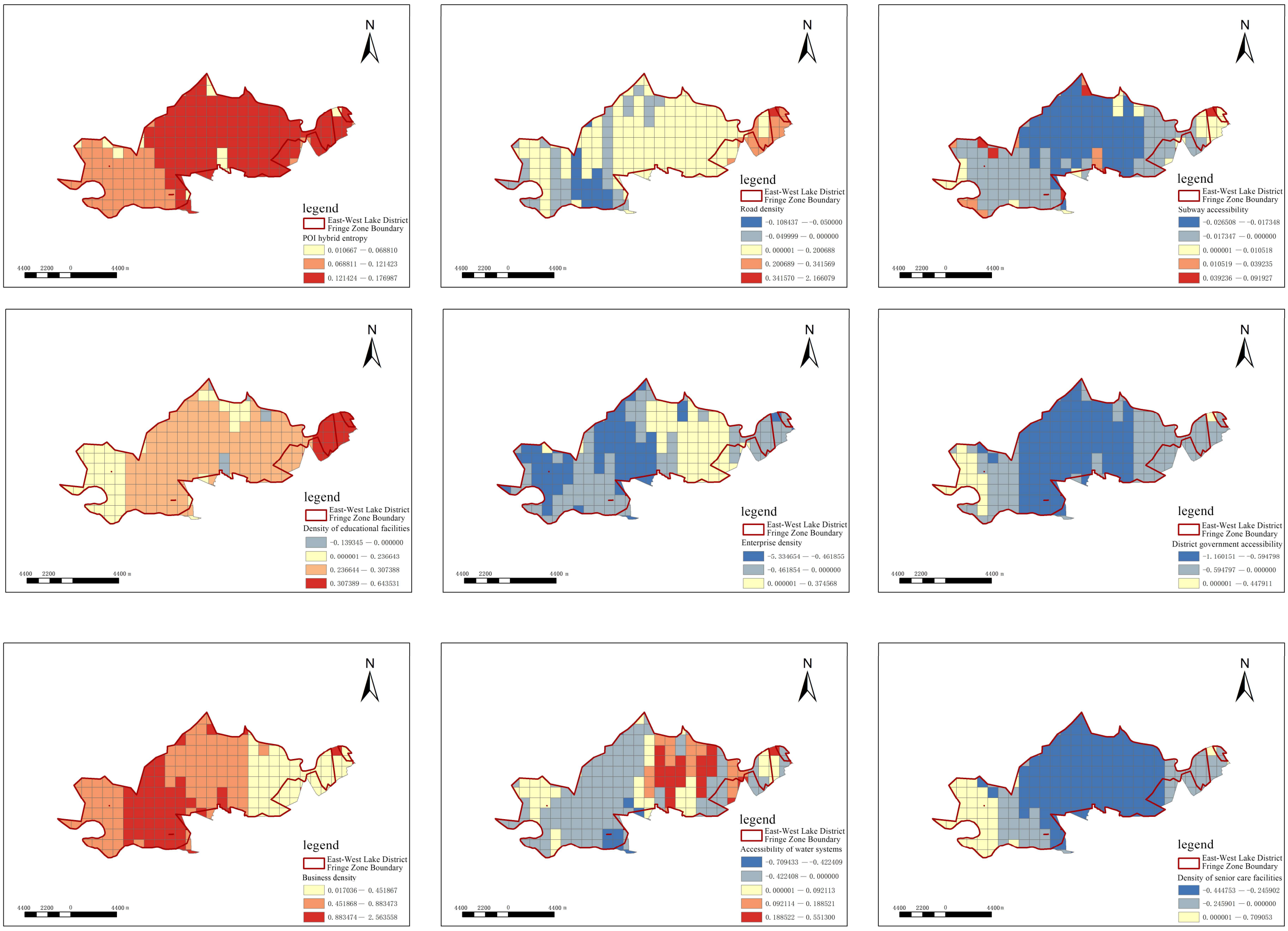


Figure 12. Coefficient plot of MGWR analysis with 2020 population size as the dependent variable for the East–West Lake District.

According to the MGWR regression results and historical image changes, subway station coverage should be increased in the entire East–West Lake area. Jinyinhu Street and Trail River Street developed rapidly during this decade, and should improve all kinds of public service support and road networks in the area; Wujiashan Street, as an old urban area, should improve the construction of public services and enhance the level of service, as well as optimize the road system. For Evergreen Street, the Cross-Strait Science and Technology Industry Management Office and Cihui Street, such as industrial zones, it is recommended to increase the enhancement of living services and commercial attractiveness. For Zomaling Street, the Food Industry Management Office, and the Bonded Logistics

Management Office, it is recommended that employment be increased and more industrial enterprises be attracted to the area, and that the road network be further improved and a subway be constructed. For Jiangjun Road Street, the main focus should be on increasing education facilities, improving education coverage, and optimizing the road structure.

(3) Xinzhou District

As shown in Figure 13, the population of Xinzhou District from 2010 to 2020 mainly grew around the Yangluo Development Zone metro station, with the maximum grid population reaching 4000 in 2010. The population of the fringe area of Xinzhou District showed a trend of vertical growth to the north and south on the basis of 2010, in which the population growth in the south was higher, followed by the north. By 2020, the majority of the regional grid population within the Xinzhou District fringe area exceeded 500 people, some of the grid population exceeded 2500 people, and very few grids had a population of no more than 500 people.

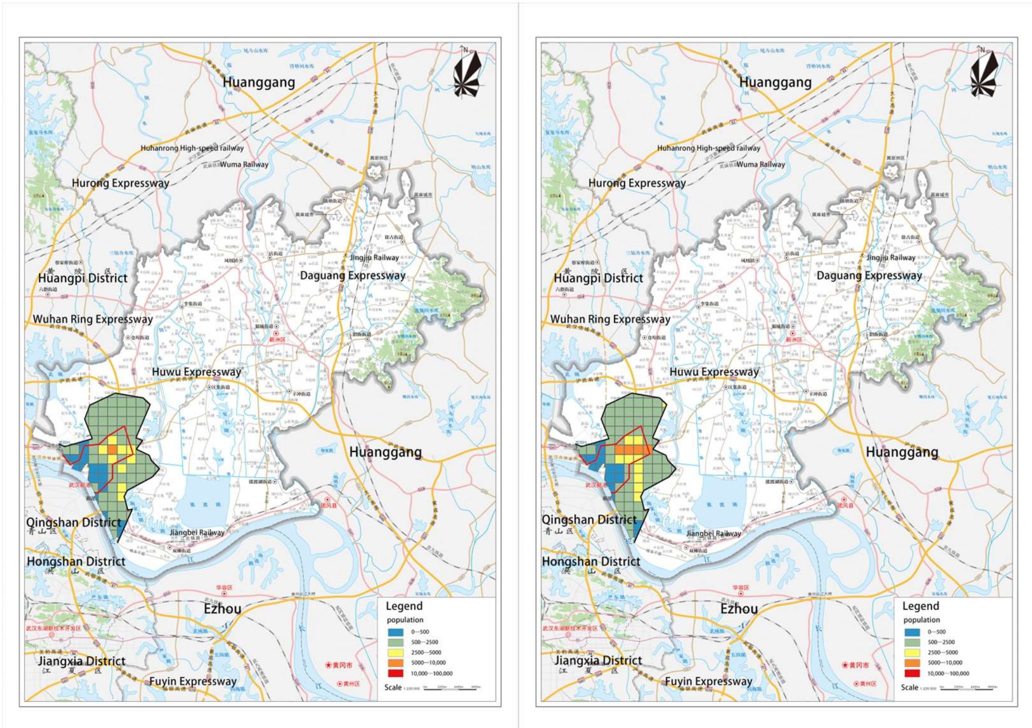


Figure 13. Evolution of the spatial pattern of population in Xinzhou District in 2010 (**left**) and 2020 (**right**).

Similar to the situation in Huangpi District, Xinzhou District is larger in area but is incorporated into a smaller area on the fringe of Wuhan City. Most of Xinzhou District is less developed, has a smaller population, has an incomplete infrastructure configuration, and is in a rural zone. During the decade, urban construction mainly occurred in the Yangluo Development Zone, followed by the area around the Zicheng Street Office.

The results of MGWR are shown in Figure 14, where population size is positively correlated with road density, education density, enterprise density, and district government accessibility across the region, of which road density, enterprise density, and district government accessibility are more strongly correlated in Yangluo Street, and education density is more strongly correlated in the southern part of Yangluo Street and Yangluo Development Zone. Subway accessibility and the density of senior care facilities have the same correlation trend as the number of people, showing a weak negative correlation in the southeast direction of Yangluo Street; POI mixing entropy shows a weak negative correlation in the northwest direction of the Yangluo Development Zone and Yangluo Street; and the density of commerce shows a weak negative correlation with the number of people. Road density, enterprise density, and district government accessibility show a strong positive correlation with population size in the eastern part of Yangluo Street, with enterprise density showing a significant performance and education density showing a strong positive correlation in the west and south.

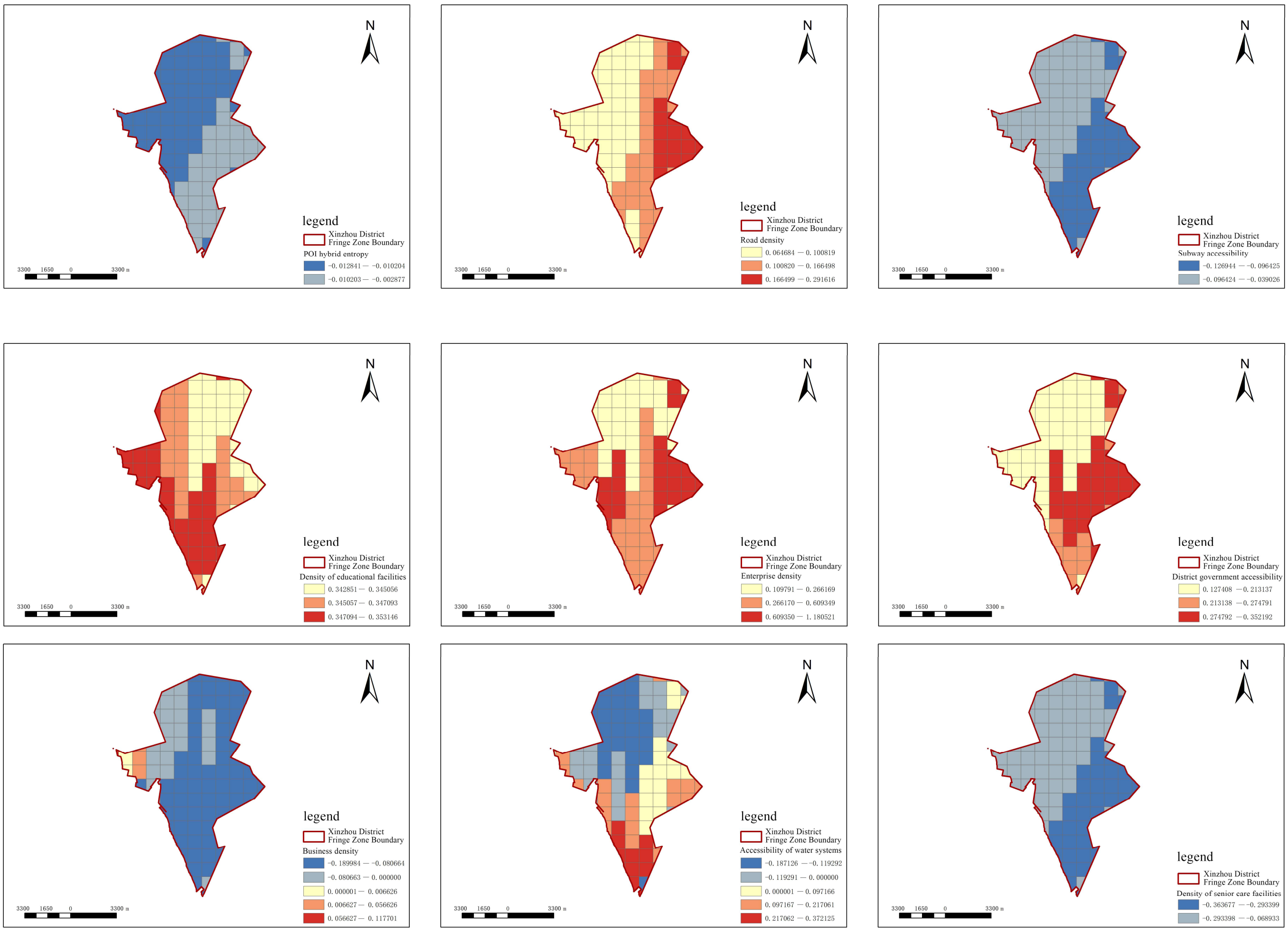


Figure 14. Coefficient plot of MGWR analysis with 2020 population size as the dependent variable for Xinzhou District.

As shown in Figure 15, the Yangluo Port area is developing towards the northeast of the city, with new residential and industrial parks linking the future Yangluo sub-city center. As one of the development centers of the region, the Yangluo Development Zone of Xinzhou District takes over the responsibility of linking the central city with the district government of Xinzhou District, which is located on the street of Mingcheng.

Figure 15. Google Earth historical images of Xinzhou District urban fringe area in 2010 (**left**) and 2020 (**right**).

According to the MGWR regression results and the Phase II historical image map, for the Yangluo Development Zone, it is recommended that the main focus is to improve the commercial service function and increase the construction of the subway to accelerate the connection with the central city. The western part of Yangluo Street should improve educational coverage, increase jobs, and improve the construction of commercial service facilities. For the eastern part of Yangluo Street, it is recommended to speed up the construction of road networks and attract enterprises to move in because the fringe area is far away from the district government of Xinzhou District, and the population attraction is mainly to take over the population of the central city to provide jobs for such a population.

(4) Jiangxia District

As shown in Figure 16, Jiangxia District has a smaller change in the scope and population size of the fringe area compared to the other five distant urban areas. In comparison, it can be concluded that the population of the fringe area of Jiangxia District in 2010 was mainly distributed in the Jiangxia Economic Development Zone Bridge New District, Miaoshan of Jiangxia Economic Development Zone, Zanglongdao Office, Fuzuling Street, Papyrus Street, and Zhengdian Street, which extended to the Jindian New District Office in 2020. The population gathering points in the fringe areas of the Jiangxia District did not change from 2010 to 2020. One gathering point was located around the Beifang Street, Zhifang Street subway line, adjacent to the Zhifang Street Office, with a gridded population that grew from 27,600 to 37,100. The area was located outside the Fourth Ring Road, surrounded by the Fourth Ring Road, Wuhan Bypass Highway, and Qingzheng Highway, adjacent to the two-day railway line, with Metro Line 7 running inside. Another gathering point was located in the Fuzuling Street Office near the Financial Port North, Fuzuling subway line, where the gridded population grew from 13,900 to 18,800, which was near the subway line 2.

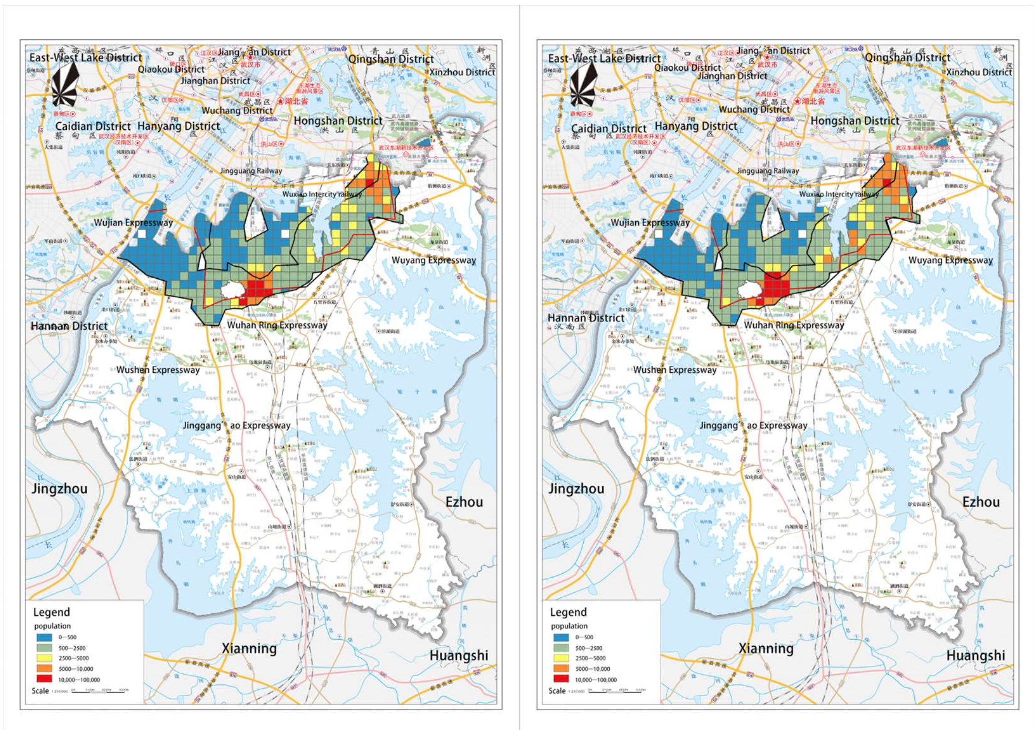


Figure 16. Evolution of the spatial pattern of population in Jiangxia District in 2010 (**left**) and 2020 (**right**).

In 2010, Jiangxia District was less developed, and most of the area was farmland and woodland, with Wuchang Avenue, Ancient Stage Road, and Cultural Avenue in Zhifang Street as the development concentration area. While the population also gathered in this area, the overall road density in Jiangxia District was low, the population density was low, and the number of enterprises and residences was small. By 2020, the built-up area of Jiangxia District expanded from the development concentration area in 2010 to the outer circle, with the greatest degree of expansion to the north and west, with vertical development in the direction of the main city of Wuhan to the north and horizontal development to the west, namely, the Yangtze River. From 2010 to 2020, Zhifang Street was the population gathering area of Jiangxia District. The area was well built with public facilities, and the transportation infrastructure, the increase in road density, and the coverage of Line 7 rail transit increased the population vitality of the area. The development of industry provided economic growth for Zhifang Street and also increased the number of jobs, which was closely related to the population. The population density of Fuzuling Street was slightly lower than that of Papyrus Street, but the development of the built environment was very rapid during this decade.

The MGWR results are shown in Figure 17, which shows that the relationship between the population size and the influencing factors in Jiangxia District is relatively complex, in which the POI mixing entropy and the population size show a positive correlation across the whole region and gradually increase from west to east; road density and commercial density show a strong positive correlation with population size in Paper Square Street, Zhengdian Street, Miaoshan Office, and Daqiao New District Office, and a negative correlation in Fozuling Street and Zanglongdao Office; education density shows a positive correlation across the region, with a stronger correlation in Paper Square Street, Zhengdian Street, Miaoshan Office, and Daqiao New District Office; enterprise density and population size show a positive correlation in Zanglongdao Office and Fozuling Street, and a negative correlation in Yifang Street, Miaoshan Office, and Daqiao New District Office; the density of senior care facilities shows a positive correlation in Yifang Street, Miaoshan Office, and Daqiao New District Office; and the accessibility of the subway shows a weak negative correlation in Zanglongdao Office and Fozuling Street.

As shown in Figure 18, the built-up area of Zhifang Street in the blue dashed box area was developed earlier and was relatively more well-constructed, which was the core residential area of Jiangxia District, while the other blue dashed box areas were all subsequently developed industrial areas. According to the MGWR regression results and historical image change maps, the western portion of the fringe area, where subway accessibility was strongly correlated with population size, struggled to increase rail construction in the near future and should increase POI mix, education, and commercial amenities to continue to increase population attractiveness. The central region should not increase the number of businesses and should take full advantage of its proximity to high-quality water bodies by focusing on increasing the density of the road network. The eastern region continues to increase the number of businesses and capitalize on the attractiveness of jobs.

(5) Hannan District

In 2010, there was no area in Hannan District that was designated as an edge area. Hannan District is far from the core area of Wuhan City, and at that time Hannan District was extremely underdeveloped and had a low population density. By 2020, the edge area of Wuhan City extended to Dongjing Street and Saimou Street in Hannan District and the population was rapidly concentrated in Hannan Avenue and Xingcheng Avenue in Saimou Street; the area was east of the Yangtze River, west of the Majing River, next to the Saimou Street Office, with Wujian Highway passing through and no subway line, and 60% of the area had over 2500 people. The gridded population of Dongjing Street was mainly in the range of 700–2500, with 30% of the regional gridded population exceeding 1500 and 40% of the regional gridded population exceeding 700. The population of the fringe area of the Hannan District is clustered in the northwest corner, with an overall trend of continuous extension to the east and south, as shown in Figure 19.

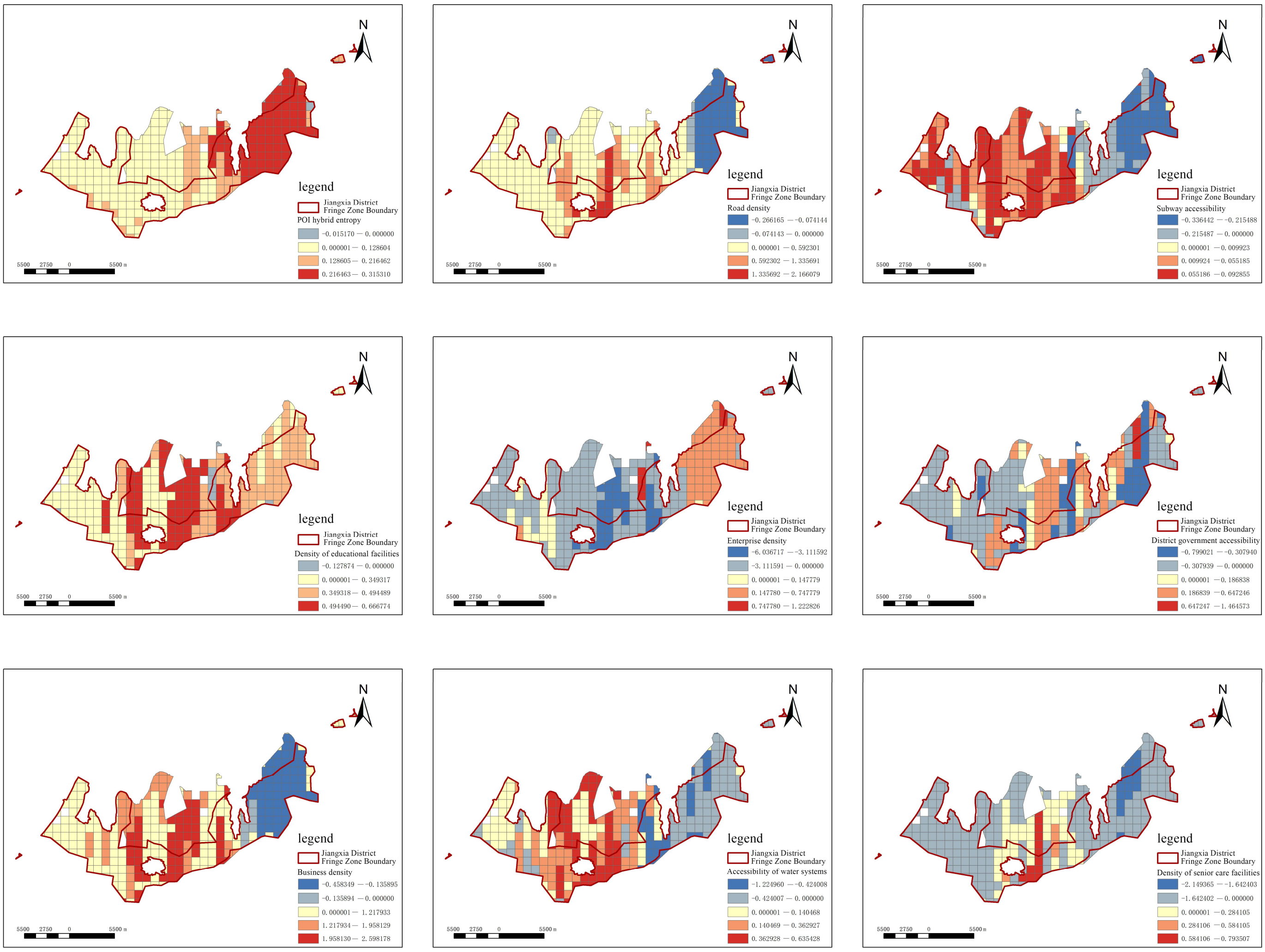


Figure 17. Coefficient plot of MGWR analysis with 2020 population size as the dependent variable for Jiangxia District.

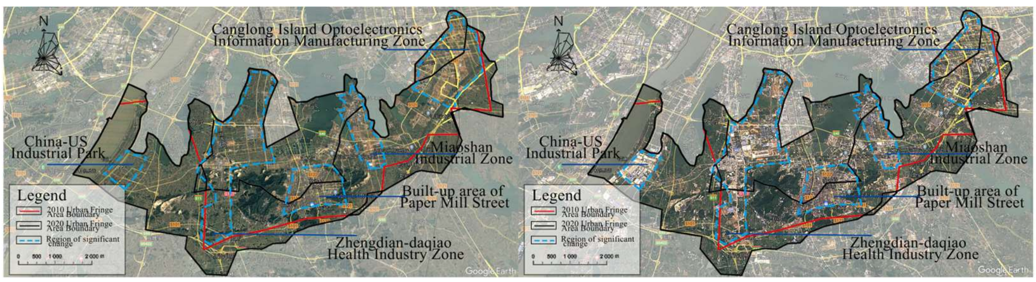


Figure 18. Google Earth historical images of Jiangxia District urban fringe area in 2010 (**left**) and 2020 (**right**).

In 2013, the Hannan District and Wuhan Economic and Technological Development Zone implemented the "unification of government and district" management, and the Wuhan Economic and Technological Development Zone hosted the Hannan District as a whole, responsible for its development and construction of Hannan District [48,49]. Shamao Street was the seat of the district government of Hannan District and the most important construction area of the district. The construction of the built environment gradually improved during the ten-year development period, including the construction of various public service facilities, among which educational facilities were added, mainly primary and secondary schools as well as kindergartens, to meet the educational needs of the region. Commercial density also increased significantly, with large-scale commercial construction and development in 2020 bringing great demographic vitality to the area compared to the small portion of commerce that was concentrated in Shamao Street in 2010. In addition to the density of educational facilities and commercial density, other elements of the built environment developed on some scale during this decade; thus, the transformation of the rural hinterland into an urban fringe was facilitated.

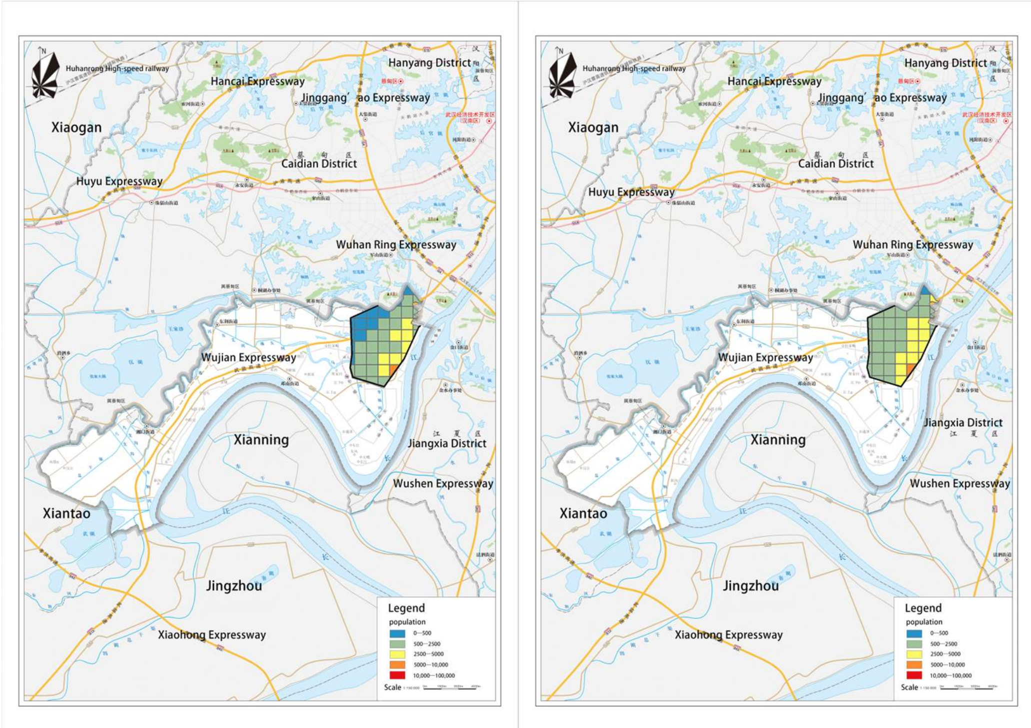


Figure 19. Evolution of the spatial pattern of population in Hannan District in 2010 (**left**) and 2020 (**right**).

The MGWR results, shown in Figure 20, show a strong positive correlation with the growth of population density in the urban fringe area of Hannan District in the northeast region, indicating that during this decade, a large number of enterprises were introduced into Hannan District, bringing better employment conditions to the region and attracting the population to move in, and these enterprises were also responsible for the construction of a large number of industrial plants in Hannan District and the formation of industrial parks of a certain scale. As shown in Figure 21, the blue dashed box area does not have a large-scale industrial zone from 2010 to 2020 but develops into an industrial park of some size. Figure 20 shows that POI mixing entropy, educational facility density, and commercial density also show a positive effect on the growth of population density in the district, and the accessibility of subway stations shows a positive correlation with population density, indicating that the construction of subway line 16 makes the area more accessible and influences the growth of the population. Overall, during the development and construction of Hannan District in this decade, businesses and enterprises were the main factors influencing the development and population growth of the area, and the opening of the subway also influenced population growth. The population growth will also promote the development of Sagami in a better direction as the new city center of Hannan District.

According to the analysis of MGWR regression results and historical image maps, the whole region should continue to increase the rail line, take advantage of the density of commercial and various types of facilities, including Dongjing Street, and prioritize the development of commercial and education. Shamao Street attracts more enterprises to move in and brings more employment opportunities to the region.

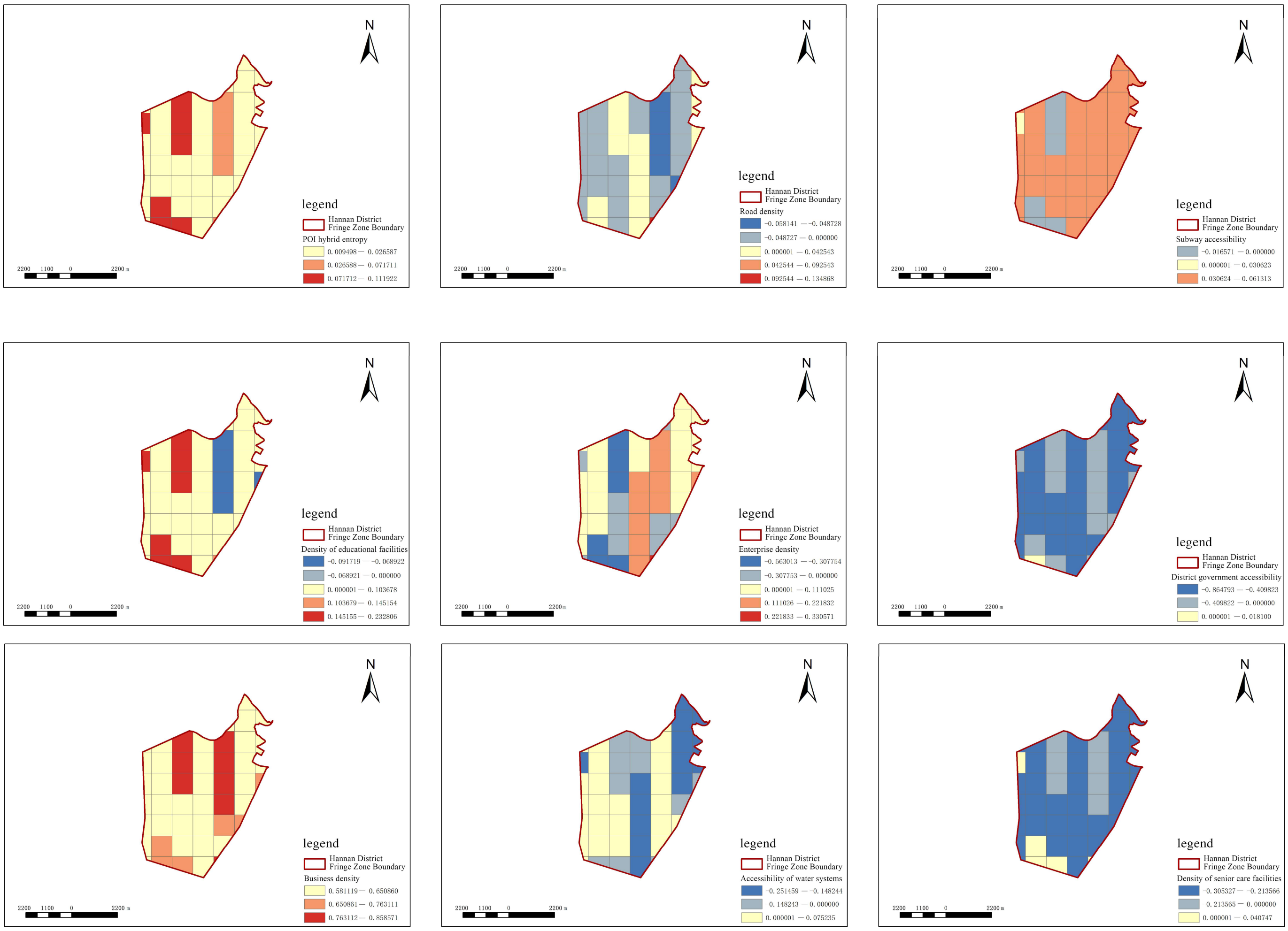


Figure 20. Coefficient plot of MGWR analysis with 2020 population size as the dependent variable for Hannan District.

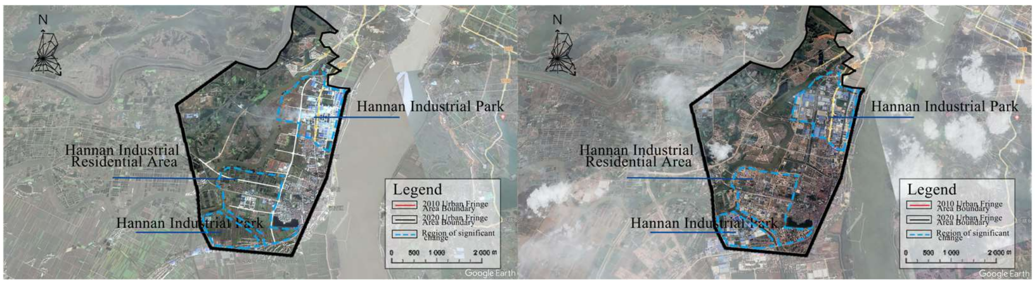


Figure 21. Google Earth historical images of the urban fringe area in Hannan District in 2010 (**left**) and 2020 (**right**).

(6) Caidian District

As shown in Figure 22, the edge area of the Caidian District expanded more from 2010 to 2020, but the growth population was smaller. The 2010 population was mainly distributed in Caidian Street, Caidian Economic Development Zone Fenghuang Mountain Office, Houguan Lake Ecological Livable New City Management Committee, in which the population gathered in Caidian Street Caidian Square, Lin Roach Avenue, and Houguan

Lake Xintian Avenue. The number of people reached 5000 in this period and the population was concentrated near the subway line and Han Cai Expressway; the Fourth Ring Road and Wuhan City Bypass Expressway passed through longitudinally. At the same time, Chaoyang Street also had some population gathering, but the population number was low, most of them did not exceed 1000 people/km^2, and a small number of grids had more than 2000 people. In 2020, the population near Caidian Square continued to grow, with the population growing to the west and south; although it extended to the streets of Zhashan and Junshan, the overall growth was not high, and most areas still did not exceed 1000 people. A new population gathering point was formed in the street office of Zhashan, south of Zhashan Lake.

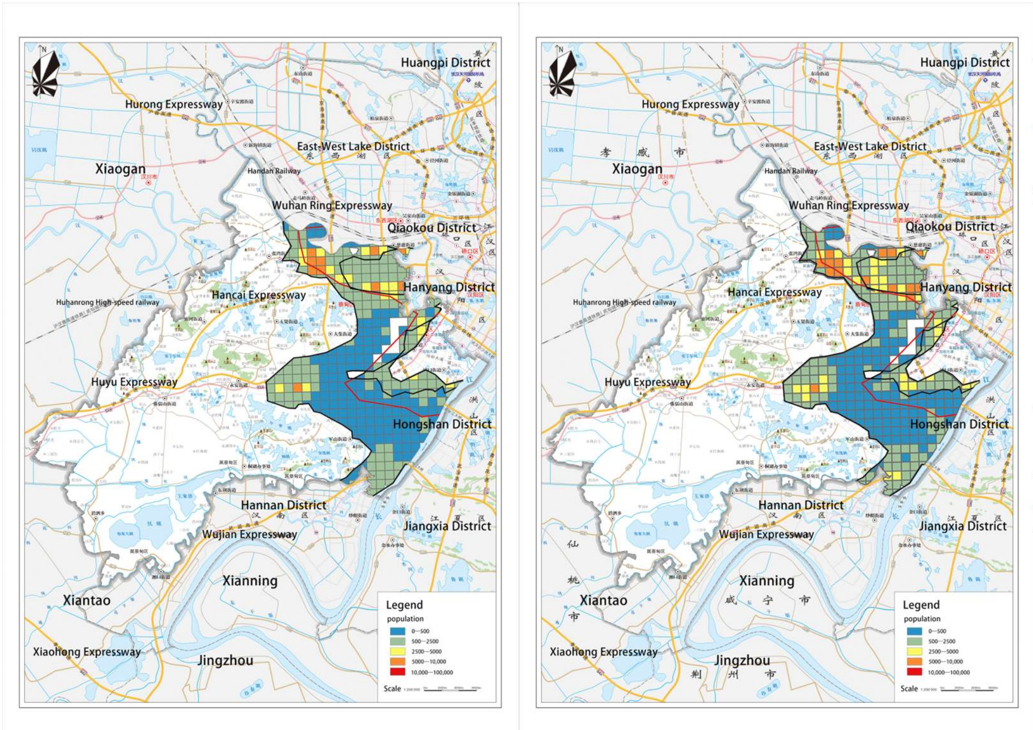


Figure 22. Evolution of the spatial pattern of population in Caidian District in 2010 (**left**) and 2020 (**right**).

Due to the large area, there are several development centers in the region, among which Caidian Street is mainly residential, Zhashan Street has developed into an industrial park connected with Changfu Industrial Park, and Sino-French Eco-City has subsequently developed into a part of the central city. The increase in the construction of various facilities for education, retirement, and commerce can be seen visually in the POI data for 2010 and 2020. The construction of some new residential areas, as well as the improvement of surrounding roads, also improved the regional traffic situation and further attracted the population. Caidian Street, after the opening of the Caidian line, further enhanced the convenience of the region. The street of Zhashan developed rapidly during this decade. Although there was still a small gap compared with the street of Caidian in the same district, the built environment still achieved massive construction development. In the new Territorial Spatial Planning, Changfu Industrial Park located in Zhashan Street was listed as the new city center of Caidian District, with huge development potential.

The MGWR results are shown in Figure 23, where POI mixing entropy and population size show a weak positive correlation in Caidian Street, Fenghuangshan Office, and Haugong Lake Eco-Livable New Town Administrative Committee, and the correlation decreases outwardly; commercial density and population size show a strong positive correlation in Zhuankou Street, Zhuanyang Street, Changfu Industrial Park, Fenghuangshan Office, and Haugong Lake Eco-Livable New Town Administrative Committee; education density and population show a weak positive correlation in the northwest corner of the fringe area, and a weak negative correlation in the area bordering the center of the city; the correlation between the road density and the number of population is gradually weakening from the east to the west, from the positive to the negative direction; the density of enterprises shows a strong positive correlation in the Daji Street and the Hougonghu Ecological and Livable New City Administrative Committee, and a strong negative correlation in the Zhangwan Street and the Fenghuangshan Office; subway accessibility shows a weak positive correlation on Yushan Street and decreases to the east; the density of senior living facilities shows a positive correlation in the densely populated northern part of the fringe area.

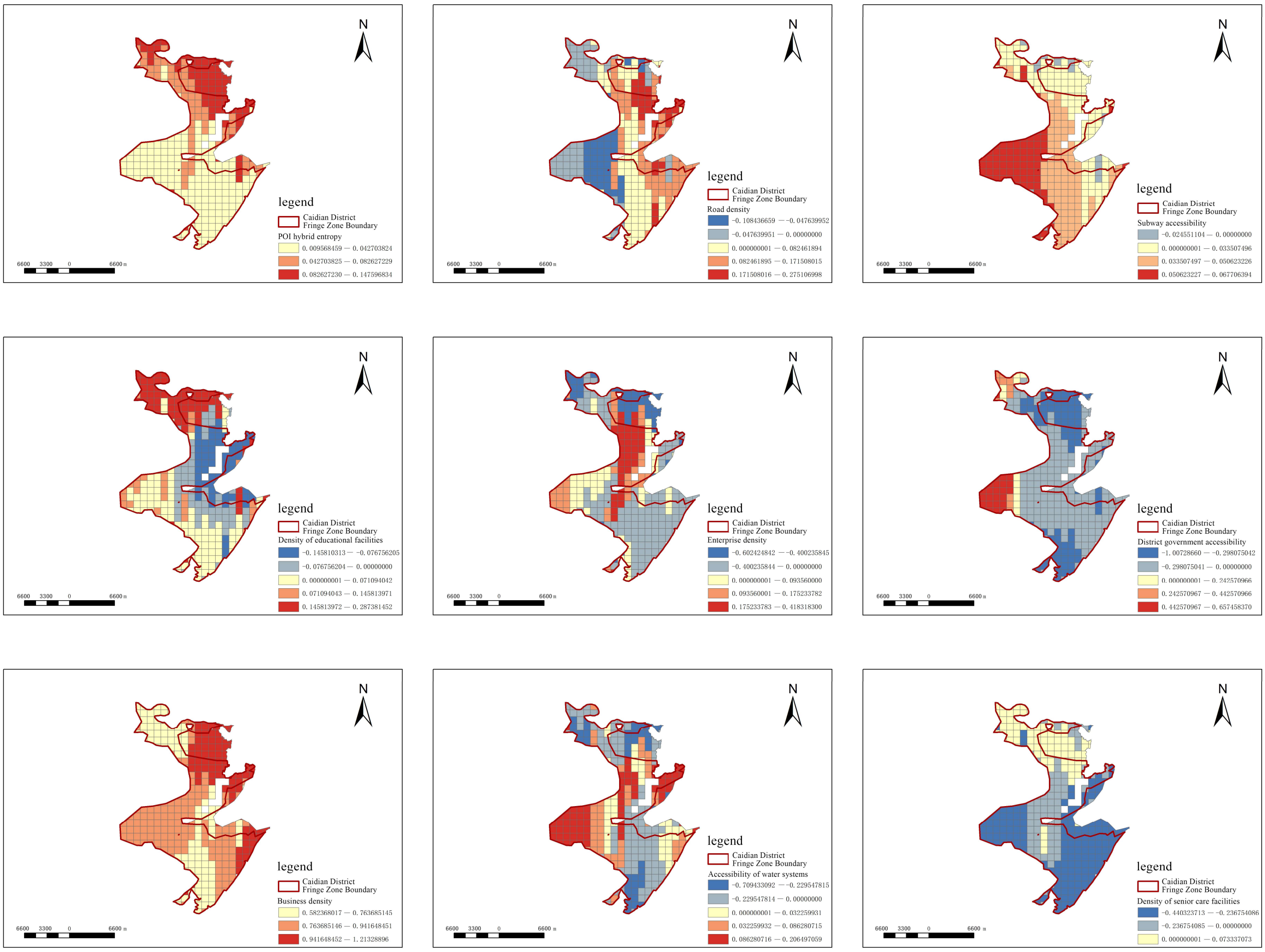


Figure 23. Coefficient plot of MGWR analysis with 2020 population size as the dependent variable for Caidian District.

As shown in Figure 24, the construction focus of Caidian District is concentrated on Caidian Street and Zhashan Street, which is now Caidian Modern City and Changfu Industrial Park. After ten years, Zhashan Street developed into an industrial park in the Caidian District, and the density of enterprises increased dramatically, bringing employment opportunities and realizing population growth. This is consistent with the results of the MGWR analysis. The regional landscape of the Caidian District is mostly a hilly lake and marsh plain dominated by ridges, with many unsuitable sites for construction. Overall, both areas in the Caidian District that realized significant population growth are closely related to the development and construction of the built environment, but the dominant factors are not exactly the same. According to the MGWR regression results and the historical image change map, for Caidian Street, it is recommended to focus on improving the education support; for Fenghuangshan Office and Hougong Lake Ecological Livable New Town Management Committee, it is recommended to improve the education support and, at the same time, increase the life service facilities, carry out commercial construction, and improve the coverage of all kinds of public service facilities; for Daji Street and Zhashan Street, it is recommended to focus mainly on the construction of industrial production zones to increase the number of enterprises and promote the development of the region's transformation, in which Zhashan Street improves the coverage of the subway; for Zhuankou Street and Zhuanyang Street, it is recommended to optimize the road structure, accelerate the connection with the central city, and drive the development of the entire region.

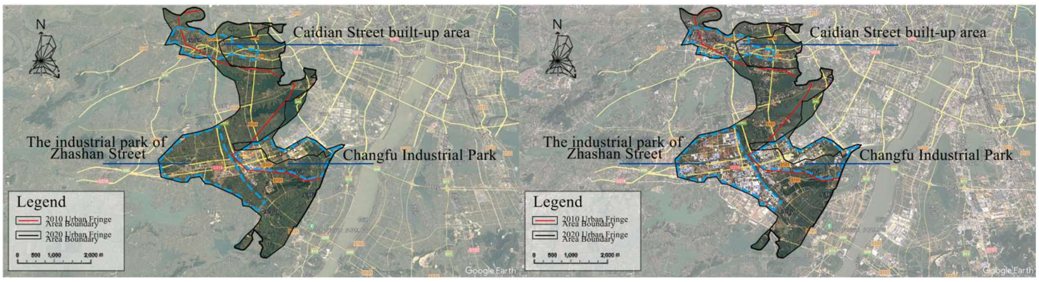


Figure 24. Historical images of the Caidian District urban fringe area in 2010 (**left**) and 2020 (**right**).

6. Conclusions

In this paper, the urban fringe of Wuhan in 2010 and 2020 is taken as the specific research object. Based on the population data and built-up environment data of the Wuhan fringe in 2010 and 2020, the spatial distribution of the population and the evolution of the built-up environment in the Wuhan fringe are statistically analyzed, and how the built-up environment affects the population quantity and spatial distribution is also analyzed. Some planning suggestions are put forward to enhance the attractiveness of the fringe population. This study provides a new perspective on megacities and supercities' central urban population relief and puts forward a set of complete methods and case studies from the analysis of built-up environmental factors, factor extraction, and screening to model analysis for the marginal areas to attract the central urban population through improved planning and construction.

6.1. Working Summary

First, the extent of Wuhan's urban fringe area during 2010–2020 was determined at three levels: impervious ground ratio, landscape clutter, and population. Second, based on the built environment '5D' theory, the built environment evaluation indexes of the study area were proposed. Then, OLS was used to preliminarily explore the correlation between population and built environment, and the population influencing factors were further screened based on significance and covariance. The screened influencing factors were used as independent variables, and the population of the far urban area was used as the dependent variable for MGWR analysis. Finally, based on the regression results, this paper interprets the relationship between the spatial distribution of the population and the built environment in the fringe districts of Wuhan, synthesizes the actual development and construction of Wuhan's urban fringe districts, and puts forward planning suggestions for attracting population to each distant urban area.

6.2. Main Conclusions

(1) In 2010, a small number of Wuhan's fringe districts were located within the administrative boundaries of the central urban area. By 2020, the fringe districts were located within the administrative boundaries of the far urban area. The development bases

and construction conditions of the far-away urban areas varied considerably, resulting in an increase in the populations of the fringe districts located in different far-away urban areas, and the magnitude of the increase varied considerably; therefore, it is necessary to put forward planning and construction proposals for the planning and construction of the far-away urban areas in line with their respective characteristics.

(2) The "5D" elements of the built environment comprehensively describe all aspects of the urban built environment, covering most of the contents of urban planning and construction, and can be used as the theoretical basis for a more comprehensive construction of urban construction factors affecting the spatial distribution of the population.

(3) First, the OLS model was used to select the significance and covariance of the variables. Then, the MGWR model was analyzed, and the adjusted R^2 reached 0.725. And the results of the analysis showed that the influencing factors searched through the "5D" theory of the built environment better explained the demographic changes in the marginal zone.

(4) Due to the MGWR's calculation results of the bandwidth of different influencing factors, it can be seen that four factors, such as downtown accessibility, sports facility density, general hospital density, and connectivity index, are global variables with relatively uniform characteristics in the whole Wuhan fringe area. The other nine factors, such as enterprise density and district government accessibility, are local variables, with different influencing tendencies in each district, and thus need to be analyzed separately and put forward different planning suggestions.

6.3. Planning Recommendations

We can make suggestions for future planning and construction in two different dimensions: global variables and local variables. The global negative correlation of the density of sports facilities better finds that a large number of sports facilities in Wuhan are chosen in the more sparsely populated areas, which is related to the fact that Wuhan has just hosted the World Military Games. And in the future, Wuhan should pay attention to the utilization of these venues, to utilize their benefits, and to drive the development of the surrounding area. The downtown accessibility shows that the development of Wuhan's fringe districts is no longer influenced by a single center, and the construction of the city's sub-centers may have more of a radiation effect. The global positive correlation between medical facilities shows the importance of convenient access to medical services. Adding hospitals in areas with a lack of medical facilities can be a good way to promote population growth. And the connectivity of the road network is a plus for promoting population growth, which is in line with the general rule of planning theory.

For the nine variables manifested as local factors, considering that each far-away urban area has its own characteristics, each far-away urban area is analyzed according to four aspects: changes in the spatial distribution of the population, results of the MGWR analysis, characteristics of changes in the fringe areas, and planning recommendations. This part has more content, which fully shows the complexity of planning and construction and also reflects the relevance of this study.

6.4. Prospects for Follow-Up Research

Further research on the relationship between the built environment and the spatial distribution of the population can be carried out from the following perspectives:

(1) The Built Environment 5D Indicator is a theoretical perspective, and the selection of specific indicators is limited by data availability, which varies from city to city and from period to period, so if researchers have access to more comprehensive data, they can also look for different influences on the spatial distribution of the population and carry out further research.

(2) The change in population size is also a topic worth studying, and subsequent studies can analyze the amount of change in the population of each grid as a dependent variable to explore the factors influencing the amount of change in the population.
(3) Wuhan is a city with a very rich geographic environment, with the Yangtze River, the Han River, and numerous lakes and mountains; the geographic environment of the fringe areas in different locations varies greatly. And its history of development is also different, coupled with the large size of the urban fringe area. However, it is very difficult to explain the spatial distribution of the population of the different far-away urban areas and the interrelationships of various influencing factors in a single article, which is limited to the length of this paper. The planning proposals for the various far-away urban areas have not been fully and completely expressed, and subsequent studies can be further analyzed in terms of subregions or sub-factors to provide more specific suggestions for the planning and construction of the city.

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