SPATIAL EQUITY OF CITY PUBLIC OPEN SPACES BASED ON G2SFCA: A CASE STUDY OF WUHAN, CHINA

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Abstract:

Urban public open spaces refer to open space between architectural structures in a city or urban agglomeration that is open for urban residents to conduct public exchanges and hold various activities, and their spatial distribution characteristics are important indicators to measure the sustainable development of urban ecological society. Therefore, it is important to evaluate the rationality of urban public open space layout for practical guidance. Address this problem, taking Wuhan as an example, this paper uses high-resolution grid population density data and web map API to construct an evaluation system for the spatial equity of urban public open spaces based on the accessibility index calculated from G2SFCA. The results showed that the layout of public open spaces in Wuhan is not reasonable, and there are significant spatial differences in the accessibility index of different types of public open spaces, as well as a certain degree of imbalance between them and the spatial distribution of population, indicating that there is a "mismatch" and "dislocation" in the supply-demand relationship of public open spaces in Wuhan. These results explain the fairness of public open space layout in Wuhan and provide a scientific basis for a more reasonable and equitable allocation of urban public open spaces in Wuhan.

1 INTRODUCTION

As an important part of urban public resources, public open space has become an important yardstick to measure the level of sustainable social development, reflect social equity and justice, and reflect governmental governance ability. Public open space has the dual characteristics of public and openness, and publicness is its fundamental value, emphasizing the openness and accessibility of urban space for different social classes and individuals. Spatial equity is derived from "social equity", which means that everyone is treated fairly, regardless of his or her position in society (Dadashpoor et al., 2016). Specifically, spatial equity of urban public development refers to the rational degree of urban public space layout caused by the variability of demand for a particular public space in different regions, i.e., whether it can ensure that all people have equal opportunities and rights to access equally allocated public open space(Omer, 2006). Spatial accessibility refers to how easy it is to overcome costs (including time, distance, cost, etc.) to reach any point in space from one place, and its distribution characteristics are one of the important factors affecting spatial fairness (Li et al., 2022). Since the evaluation method of spatial accessibility can identify the scarce areas of public open space, it is an effective way to measure the fairness of public open space (Gu and Yi, 2010).

Currently, spatial accessibility research methods have been widely applied to evaluate the spatial equity of public service facilities such as parks, medical care, schools, and shopping centers(Song et al., 2010). There are many spatial accessibility research methods(Li and Lu, 2005), mainly the buffer distance method, cost-weighted distance method, network analysis method, and two-step moving search method. Among them, the

Two-Step Floating Catchment Area Method was first proposed by Radke and later refined by Luo and other scholars (Tao and Cheng, 2016), and gradually developed into a more mature accessibility model, which integrates non-spatial attributes into spatial accessibility research and takes into account the scale of supply points, the scale of demand points, and the interaction between supply and demand points in the process of calculating accessibility, so this method is more valuable in evaluating the spatial accessibility of public service Therefore, this method is of high value in evaluating the spatial accessibility of public service facilities (Liu et al., 2007). Since then many scholars have improved it and applied the modified two-step moving search method to accessibility evaluation in various fields (Deng et al., 2016 , Tao et al., 2015 , Zhang et al., 2015 , Hu et al., 2012). Among them, the gravity-based two-step search method (G2SFCA) introduces distance decay coefficients, which can reflect the variability of different areas in reaching public service facilities in the evaluation of spatial accessibility, so the accessibility evaluation results of this method are more reliable.

A good layout of public open space enables cities and regions to function efficiently and equitably. In addition, public open spaces can improve the quality of life of urban residents, promote social inclusion, and foster ecological and social productivity sustainability (Jalaladdini and Oktay, 2012). Considering the importance of urban public open space, many scholars have conducted qualitative and quantitative analyses on the equity of urban public open space from different levels and multiple perspectives. Some scholars (Chen et al., 2020) and others have quantitatively analyzed the distribution of urban public spaces from the perspective of spatial agglomeration

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degree and agglomeration pattern, and have made valuable suggestions for creating popular and ecological urban public spaces. Some other scholars have divided different social classes in terms of urban residents' income, age and race, and have conducted extensive research on the fairness of public space distribution among different classes, advocating the importance of environmental equity, which can help reduce inequality in urban public space. However, few scholars (Bahrini et al., 2017) have analyzed the spatial differentiation pattern of each component of urban public open space, and most studies are limited to some areas of public open space such as parks, squares, and green areas for spatial distribution analysis and environmental evaluation. However, in the face of rapid urbanization today, it is urgent to solve the problem of public space in congested areas and improve the quality of life of urban residents. Therefore, the overall analysis of each element of public open space is of great significance to improve the living standard of residents and promote sustainable urban development.

To sum up, public open space is an indispensable component of the city. Given that all elements of public open space are indispensable, this paper combined the actual situation and available data of Wuhan city and adopts the G2SFCA to calculate the accessibility of public open space in seven central urban areas of Wuhan city from the image element scale, and on this basis, analyzes the layout of public open space in equity, to provide technical support for the quantitative assessment of the sustainable development goals of building accessible and green public open spaces.

2 DATA AND METHODS

2.1 Study Area

Wuhan is located in central China and is the capital of Hubei province and a national central city. This paper takes the main urban area of Wuhan as the study area, which includes seven district-level units under Wuhan City, including Jiangan District, Jianghan District, Qiaokou District, Hanyang District, Wuchang District, Qingshan District, and Hongshan District, with an area of about 965 square kilometers (Figure 1).
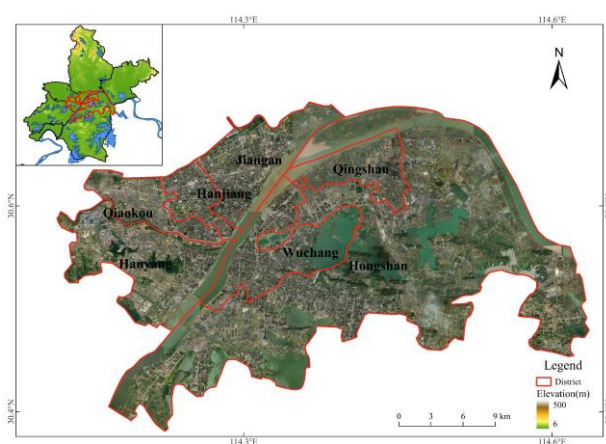

Figure 1. Study Area.

2.2 Data Source

2.2.1 Open Spaces: Urban public open space refers to the open space between the building structures of the city, which is open for all city residents to carry out public communication activities (Chen and Ye, 2009). In this paper, public open space is divided into two parts, one is green space, including comprehensive

parks, community parks, green areas, campgrounds, etc.; the other is gray space, including city squares, commercial streets, etc., as shown in Table 1. The research data are obtained from the 2022 Gaode Map Wuhan central city POI data, which are collected through the search API tool of Gaode Open Platform, and the main data collected include information such as name, facility category, and latitude and longitude, while the data are subject to coordinate correction, and the results are shown in Figure 2.

Major Categories	Minor Categories	Quantity	Percentage
Green Spaces	parks, recreational green areas, campground	257	25.7%
Grey Spaces	City Square, Commercial Street	742	74.3%

Tabel 1. Number and proportion of green space and gray space POIs in the central city of Wuhan.
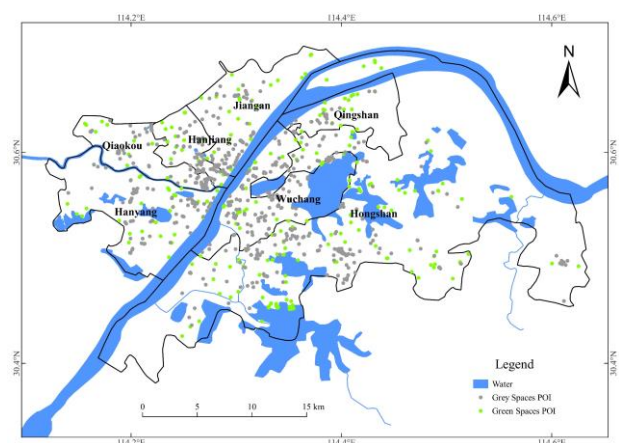

Figure 2. Distribution of public open space in the central city of Wuhan.

2.2.2 Population Data: The equity of public space is not only related to the properties of public space such as class, area, and layout, but also the spatial differences in the demand of the population in the area. The population grid data reflects the spatial variation of population size, and to a certain extent, it can represent the spatial distribution of potential demand for public open space. Therefore, this paper uses the Worldpop 2020 gridded population dataset to reflect the spatial distribution of Beijing's population at a relatively fine-scale. This dataset has a spatial resolution of 100m and is corrected to match the total population of each country in the official United Nations population estimates (UN 2020), and is widely used for refinement studies of areas with medium and high population density(Stevens et al., 2015).

Figure 3 shows that the population density in the central city of Wuhan is unevenly distributed. The areas with higher population densities are mainly concentrated in Qiaokou District, Wuhan City and Wuhan City. The areas with higher population density are mainly concentrated in Qiaokou District, Jianghan District, Jiangan District, and Wuchang District, while the population in Hongshan District and Qingshan District is uneven. Jianghan District, Jiangan District, Wuchang District, while the population density in Hongshan District and Qingshan District is smaller. The population density of Hongshan District and Qingshan District is smaller. The spatial distribution of population in the study area shows a more obvious distribution, without considering the barrier of natural water bodies. The

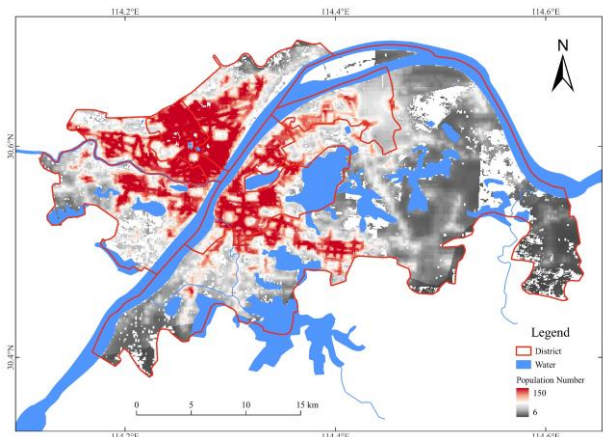spatial distribution of the population in the study area shows a more obvious pattern of circles and layers.

Figure 3. Spatial distribution of population size

2.3 Methods

2.3.1 G2SFCA: The accessibility of public open space is not only affected by its distance from the demand unit but also closely related to the demand scale of the demand unit. The higher the demand around the supply point and the busier the supply point, the less "accessibility" of the service may be, which leads to lower accessibility. The two-step floating catchment area (2SFCA), first proposed by Radke and Mu(Radke and Mu, 2000) in 2000, calculates the supply-to-demand ratio within a certain search radius, taking into account residents' competition for limited resources.

However, this method assumes that all residents in the search area have equal access to services, which is somewhat different from reality. G2SFCA adds a distance attenuation coefficient to 2SFCA, which can more accurately reflect the characteristics of accessibility with distance attenuation. In this paper, the public space POI data is overlaid with the population grid data, the raster image element where the public open space POI is located is used as the supply unit, and the effective image element of the population grid data is used as the demand unit, and G2SFCA is used to calculate the accessibility of public space.

First, the supply-demand ratio of the public space is calculated. Suppose a rectangular area with a side length of 100 image units (10 km) is centered on supply unit j in the search area, and there are n demand units in the search area. The competitive advantage of each demand unit is determined by its distance cost to the supply unit and the demand side, from which the following supply-to-demand ratio R_j is calculated for supply unit j.

$$R_j = \frac{S_j}{\sum_{i=1}^{n} G(d_{ij})P_i} \qquad (1)$$

where S_j is the supply scale of the supply unit, due to the lack of relevant data, this paper assumes that the supply scale of each supply unit is the same and takes unit 1 uniformly;

P_i is the demand side of the demand cell, i.e. the population size;

d_{ij} is the distance between the demand cell i and the supply cell, calculated as described in section 2.3.2;

$G(d_{ij})$ is the Gaussian decay function considering the spatial friction factor, and the most common power function is used in this paper, whose specific form can be expressed as:

$$G(d_{ij}) = d_{ij}^{-\beta} \qquad (2)$$

where $G(d_{ij})$ is the distance decay function;

d_{ij} is the distance between demand point i and supply point j;

β is the distance decay parameter, which is taken as 2 here.

Then, the reachability of each demand unit is calculated. With demand unit i as the center, search for its reachable supply units in the search area, calculate its distance weight $G(d_{ij})$ from the supply unit, and weight the sum of the demand ratio R_j of the supply unit according to the distance weight to obtain the reachability of each demand unit.

$$A_i = \sum_{j=1}^{m} G(d_{ij})R_j \qquad (3)$$

where $G(d_{ij})$ is the Gaussian decay function considering the spatial friction factor;

R_j is the supply-to-demand ratio calculated from step 1.

The public open space accessibility scores calculated in G2SFCA are dimensionless values. To observe the fairness level of the whole study area, accessibility is divided into six categories in this paper, which correspond to the six cases of saturated supply, sufficient supply, balanced supply and demand, insufficient supply, lack of supply, and no supply of services, as shown in Table 2.

Range of Accessibility value	Supply and demand status	Spatial equity
$A_i = 0$	No supply	High inequity
$0 < A_i < 0.1$	Weak supply	High inequity
$0.1 \leq A_i < 0.3$	Under supply	Relative inequity
$0.3 \leq A_i < 0.5$	Supply balance	Equity
$0.5 \leq A_i \leq 1$	Adequate supply	Relative equity
$A_i > 1$	Over supply	High inequity

Tabel 2. Supply and demand status and equity meaning.

2.3.2 Distance metric based on raster map: In this paper, the distance between the supply and demand units within the study area is calculated in the form of a raster map, as shown in Figure **4**.

Both supply and demand units are represented by raster images, and the distance between them is the sum of the movement cost of each path between them. The path has two directions, vertical and horizontal, and the movement cost of the water body image element and non-water body image element are 3 and 1 respectively.

What's more, A* algorithm is used to plan the optimal path between demand and supply units, i.e., the path with the smallest sum of movement cost. Compared with the distance metric based on the vector road network, the distance metric based on a raster map is simple and convenient to calculate, requires low data accuracy, and has better adaptability with population grid data, which is more suitable for large scale distance metric.
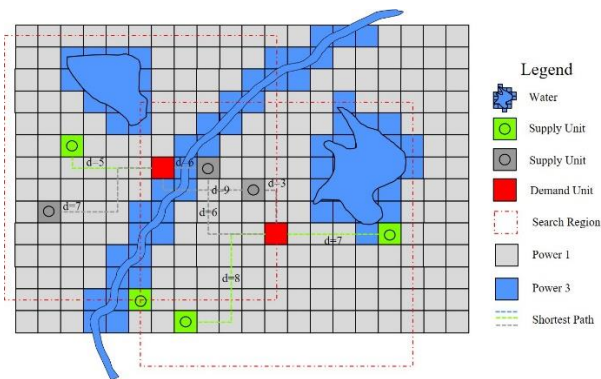
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Figure 4. Distance metric based on raster map

3 RESULTS

3.1 Spatial differences in accessibility of different types of public open space

The calculation results of the fairness of different types of public open spaces in Wuhan are shown in Figure 5. There are significant spatial differences in the accessibility of public open spaces in Wuhan. For green space, as Wuhan is the "City of Thousands of Lakes", there are many lakes, and most of the parks and green spaces are built based on planning for lakes, so the "Over supply" and "Adequate supply" Most of the areas are near lakes and rivers. On the contrary, as the population clusters are far away from lakes and rivers, the distribution of green space is less, and there are more cases of "Weak supply" and "Under supply". In the southern part of Wuhan, the distribution of green space is large, and the population density is relatively low, so it is mostly in the state of "Over supply" and "Adequatet supply". While the eastern and western areas of Wuhan have the lowest population density, the distribution of green space is also the most sparse, so they are mostly in the state of "Weak supply" and "No supply".

As for the gray space, it is mostly distributed in the areas with high population density in the built-up areas of the city, so the fairness of the gray space is better in the areas with concentrated population distribution, and it is mostly in the state of "Over supply" and "Adequate supply". However, in the less densely populated areas in the northeast and southwest of Wuhan, there is no gray space distribution, so it is mostly in the state of "Weak supply" and "No supply".

For the public open space that considers both green space and gray space, the spatial agglomeration of equity is significantly weakened, and the overall equity is better. However, in the northeast and southwest of Wuhan city center, although the population density is low, there is no public open space distribution, so the accessibility is poor, and the overall situation is "no supply service".

In addition, in addition to the large areas with high accessibility, there are also a number of smaller areas with high accessibility in the four districts north of the Yangtze River. This indicates that the public open spaces in these areas are mostly scattered, and the overall spatial balance is poor, and the coordination between them is not obvious. Therefore, the construction of public open space in the central city of Wuhan should pay attention to the spatial balance to ensure that each area can receive public open space services that match its needs.
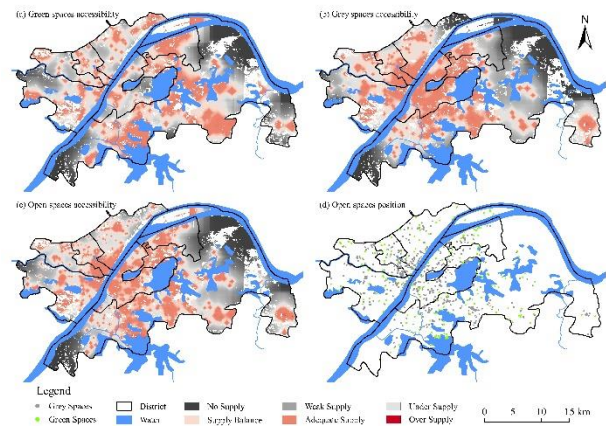

Figure 5. Evaluation results of spatial equity in the study area

3.2 Spatial autocorrelation analysis of accessibility of public open space

In this paper, the public open space in the central city of Wuhan was analyzed using the global spatial autocorrelation analysis method, and the results are shown in Table 2.

The Global Moran's I of all types of public open spaces is greater than 0, and the Z-Sorce is much greater than 2.58, indicating that there is a significant clustering effect in the spatial distribution of public open spaces in Wuhan. Among them, the Global Moran's I of green spaces is the smallest, which indicates that the clustering effect of green spaces in Wuhan is weak in spatial distribution. This is since green spaces are mostly built around lakes, the distribution of lakes in Wuhan is angular, and the Yangtze River runs through the center of Wuhan, so the distribution of green spaces is more scattered. Global Moran's I of gray space is the largest, which indicates that the clustering effect of gray space is the strongest. This is mainly since gray spaces are mostly located near urban residential areas and are more concentrated in distribution.

Spaces	Spatial Autocorrelation Analysis		
	Global Moran's I	Z-Sorce	p-Value
Green Spaces	0.282445	512.19	0.000
Grey Spaces	0.453096	621.31	0.000
Open Spaces	0.352483	636.57	0.000

Tabel 3. Statistic results of spatial global autocorrelation analysis.

3.3 Hot spot analysis of accessibility of public open space

In this paper, the spatial accessibility of public open space in the study area is analyzed using hotspot analysis (Getis-Ord Gi*), and the results are shown in Figure 6.

From the figure, it can be seen that the green spatial hotspot areas are discrete distributed along the rivers and lakes, and the natural scenery of the area is conducive to the construction of park green spaces. The hot spots of gray space are concentrated in the center of Wuhan city, and the distribution is more extensive. The cold spot areas of both green space and gray space are mainly distributed in the northeast and southwest areas, but the cold spot areas of gray space are more extensive. Because of the cold and hot spot pattern of public space in Wuhan, the construction of green space should pay more attention to the inner part of the

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city, and the gray space should be appropriately expanded to the suburbs of the city.

In general, the hot spot areas of public open space in Wuhan are more consistent in spatial distribution with the concentrated population distribution areas, but the overall service level of public open space in Wuhan is poor due to the large difference in spatial agglomeration effect of different types of public open space. In the future planning and layout of public open space in Wuhan, we should focus on the cold spot areas in the eastern and western regions of the central city, promote the construction of gray spaces in the suburbs, and at the same time build small, travel-friendly green spaces within the city.
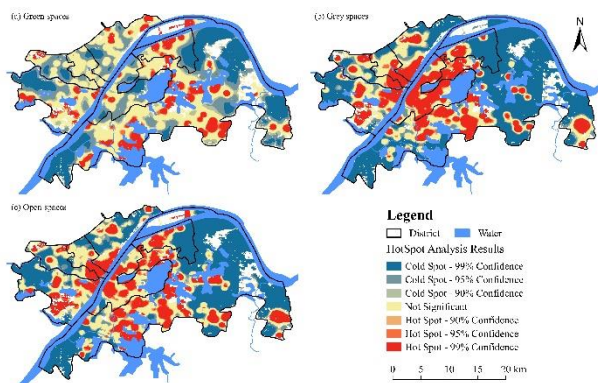

Figure 6. Study area hotspot analysis results

4 DISCUSSION

This paper mainly uses spatial equity based on physical distance to explore the distribution of public open space in the central city of Wuhan, without considering residents' demand for travel time and ignoring the differences in the demand for public open space among residents with different demographic and sociological characteristics such as gender, age and income. True spatial equity should meet the demand of residents for the shortest travel distance while meeting the demand for public open space of different groups of residents. In the planning and layout of public open space, it is more important to fully consider the real situation of different groups' willingness to use public open space.

In addition, due to the limitation of obtaining population data, this paper adopts the spatial resolution of 100m population grid data from remote sensing inversion to reflect the spatial changes of population quantity. In reality, the population is mainly concentrated in the buildings of residential communities. If more accurate population data can be obtained, the accuracy of the research results can be improved.

What's more, this paper adopts the distance metric based on raster map to calculate the distance between supply and demand units. Although this method can be well combined with the grid population data and is suitable for large scale studies, the calculation results are coarse and the accuracy of the results is poor in cities with complex surface environments. Therefore, the distance between supply and demand units can be estimated by using the road network distance with higher accuracy in future studies.

Finally, in this paper, the geometric center of public open space is studied as its entrance, assuming that all directions of public open space are accessible. Therefore, more accurate information about the entrances of public open space should be obtained in future studies to make the research conclusions more reliable. In addition, there is a competitive relationship between different scales and types of public openness, which needs to be further studied and explored in the future.

5 CONCLUSIONS

This paper explores the public open space fairness in the central city of Wuhan based on the image metric scale. In the study, the influence of distance decay on spatial fairness is considered, so the gravity-based two-step moving search method with distance decay coefficient is used to study the spatial fairness of different types of public open spaces and their differences, and the main conclusions are as follows:

(1) There are significant spatial differences in the spatial equity of public open space, and there are also significant differences between the spatial equity of different types of public open space. Green spaces are mostly distributed along rivers and lakes and are relatively scattered, but they are far away from populated areas, so the spatial equity is poorer within densely populated cities. The gray spaces are mostly distributed near urban residential areas and are more concentrated, but less distributed in suburban areas with lower population density, so the spatial equity of suburban areas is poorer. In general, there is a certain "mismatch" and "dislocation" in the relationship between the supply and demand of public open space in the main city of Wuhan.

(2) The spatial autocorrelation results of public open space accessibility show that the spatial agglomeration effect of public open space accessibility in Wuhan is significant. Specifically, the clustering effect of accessibility of gray space is greater than that of green space.

(3) From the results of the hotspot analysis of public open space accessibility, the hotspots of green space are mostly located along the rivers and lakes in the suburbs, with a small range. The hotspots of gray space are mostly located near the residential areas in the city center, with a larger distribution range and a concentrated and continuous distribution.

On the whole, the spatial equity of public open space in the central city of Wuhan is poor. The layout areas of various types of public open spaces should be arranged scientifically, their quantity should be planned reasonably, and the spatial inequity between the green spaces in the city center and the gray spaces in the suburbs should be weakened. Overall, the results of the study can identify areas of tension between supply and demand for public open space in Wuhan, and provide a scientific basis for a more rational and equitable layout of public development space in Wuhan.

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