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Accessibility and Equity of Park Green Spaces: Considering Differences in Walking Speeds Across Age Groups

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Abstract: Previous studies on measuring the accessibility and equity of park green spaces (PGSs) often overlook differences in walking speeds across age groups, which may lead to research results that deviate from actual conditions. This study expands the current literature by investigating whether ignoring age-related differences in walking speeds affects the measurement of PGS accessibility and equity. The Gaussian Two-Step Floating Catchment Area (G2SFCA) method, along with the Lorenz curve and Gini coefficient are used to measure and evaluate the accessibility and equity of PGSs in Wuhan, China, taking into account both average walking speed and variations in walking speed across different age groups. This empirical study reveals significant spatial disparities in walking speeds across Wuhan's districts, ranging from 77.2 to 78.55 m per minute (m/min), with urban areas having faster walking speeds than suburban areas. This study finds that ignoring variations in walking speed across age groups leads to an overestimation of PGS accessibility and equity in Wuhan. Furthermore, regardless of whether average walking speeds or age-specific walking speeds are considered, spatial disparities in PGS accessibility remain evident, with urban areas demonstrating significantly better accessibility compared to suburban areas. Additionally, small changes in walking speed differences between age groups (−3% to 3%) have minimal impact on accessibility and equity results, demonstrating low sensitivity to variations in speed differences among groups. Overall, scholars and policymakers should consider differences in walking speeds among various populations when planning public facilities such as PGSs to ensure stronger policy support for vulnerable groups and achieve the goal of social equity.

Keywords: park green spaces; spatial accessibility; equity; age groups; walking speeds

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1. Introduction

Park green spaces (PGSs) are critical for improving residents' quality of life, providing spaces for recreation, fitness, and social interaction [1–3], while also contributing to environmental sustainability [4]. Many countries have implemented policies to ensure that residents can access PGS within a short walking distance, such as 15 min in China [5], or within a distance threshold of 1 km in the UK [6]. However, several studies have demonstrated that vulnerable groups (e.g., children and the elderly) face reduced mobility, which limits their access to public services [3,7]. According to the World Health Organization [8], between 2015 and 2050, the ratio of the world's population over age 60 will almost double, increasing from 12% to 22%, with around 80% of elderly people residing in developing countries [9]. For example, China's elderly population is projected to reach 366 million by 2050, comprising one-third of its total population [10,11]. Given this demographic shift, more refined analyses of PGS accessibility and equity are essential to improve service quality and optimize public service planning.

Accessibility to public services, including PGSs, is a multidimensional concept typically assessed through factors such as spatial proximity, ease of access, and availability [12–14].

This study considers accessibility from a spatial perspective, often measured by the distance or time required for individuals to reach a service [15], as well as the quality and quantity of services available within that range. Various methods have been developed to evaluate PGS accessibility, including the statistical index method [16–18], the buffer method, the proximity method [19], and gravity-based models [20–22]. The statistical index method focuses on the overall park area, per capita green space, or the number of parks in a region. The buffer method represents accessibility by creating service areas within a specified distance or travel time from supply or demand points. The proximity method measures accessibility by calculating the distance or travel time from residential areas to the nearest green space. The gravity-based method accounts for spatial interactions between service providers and demand, typically incorporating a distance decay function to reflect diminishing accessibility with increasing distance. Among these methods, the two-step floating catchment area (2SFCA) method [23] and its extension, the Gaussian Two-Step Floating Catchment Area (G2SFCA) method, a special form of gravity model, have become widely used for evaluating spatial accessibility to various public services [24–26].

Regarding equity in access to public services, there is currently no unified definition or widely accepted measurement method [27–29]. In general, most previous studies on equity in access to PGSs have primarily focused on the spatial disparities and distribution of PGSs across communities [30]. Moreover, equity in public service access extends beyond spatial proximity, encompassing the fair distribution of resources to ensure services are accessible to all, regardless of socio-economic status, age, physical ability, or type of green space [31–34]. Achieving equity requires addressing the specific needs of vulnerable groups, who may otherwise face exclusion from essential public spaces due to reduced mobility [35]. Existing studies often use the Lorenz curve and Gini coefficient to assess disparities in the distribution of public service facilities and resources [36,37]. Spearman's and Kendall's rank correlation coefficients have also been applied to quantitatively assess the relationship between PGS demand and accessibility [38]. A current study [29] combines landscape ecology, spatial syntax, and GIS technology to develop a model for analyzing the spatial accessibility and equitable distribution of PGSs. Some researchers use islets, which serve as fragmented green spaces that promote equity and enhance the complexity of green spaces, fostering equitable access [33]. Overall, this study focuses on PGS equity from the perspective of spatial accessibility, emphasizing differences in ease of access to services across various areas or groups.

A limitation of existing studies is that they often overlook how variations in walking speeds among different groups affect the measurement of PGS accessibility and the assessment of equity, despite walking being the primary mode of commuting for residents accessing PGSs. Most studies on PGS accessibility typically focus only on the average walking time to destinations [39], or consider different modes of transportation [40,41] or types of green space functions [42]. While some studies have accounted for differences in walking speeds between elderly populations and other groups [43,44] when measuring PGS accessibility, they have not explained how variations in walking speeds among age groups influence accessibility and equity evaluation outcomes. With the intensifying trends of aging and low birth rates in many countries, ensuring that vulnerable groups, such as the elderly, have access to public service facilities like PGSs will become a key issue of concern for society.

The aim of this study is to address the gap in current research by investigating whether ignoring walking speed differences across age groups affects the measurement of PGS accessibility and equity outcomes, particularly in an aging society. This study aims to provide a more accurate and detailed assessment of PGS walking accessibility and equity. The research objectives are as follows: (1) to measure the walking accessibility of PGSs based on both average walking speeds and group-specific speed variations, (2) to explore the equity characteristics of PGSs based on accessibility results, and (3) to assess how walking speed differences across age groups impact accessibility measurements and equity evaluations. Wuhan, the largest city in central China, is chosen as the empirical study area due to its representative and severe aging population issue.

The remainder of this study is organized as follows: The next section presents a methodology section, which introduces the study area and outlines the methods employed in the research, followed by details of the results. Then, the study concludes with a discussion of the key findings and their policy implications. A conclusion section summarizes the research at the end of the article.

2. Materials and Methods

2.1. Study Area

Wuhan, the capital city of Hubei Province in central China, spans an area of about 8569 km^2. The city is divided into 13 districts, with 7 districts forming the main urban area and 6 districts comprising the suburban region. As the largest city in central China, Wuhan has a diverse population with a complex age structure, characterized by significant aging trends. Wuhan had a total permanent resident population of 1.576 million aged 65 and above at the end of 2023, accounting for 16.6% of the population—an increase of 8.47% compared to 2010, indicating a deepening trend of aging [45]. In addition, the population in Wuhan aged 0–14 accounted for 13.05% in 2023, representing a 3.07% increase compared to 2010 [45].

In terms of green space resources, Wuhan had over 700 wetland and urban parks by 2020. According to the 14th Five-Year Plan, the city aims to increase the total number of parks to over 1000 by 2025, with the goal of becoming a "National Ecological Garden City" [46]. Despite this planned growth, the total amount of developed parkland remains limited, and its spatial distribution is highly uneven. These disparities make Wuhan a representative case for studying issues related to PGS accessibility and equity in large Chinese cities. Consequently, this study selects Wuhan as its case study area.

2.2. Research Framework

The research framework of this study is outlined in Figure 1. First, PGSs are classified according to their size and supply capacity. The residential population of each district, categorized by age and gender, is considered as representative of the potential demand for these PGSs. Second, spatial accessibility is calculated using the G2SFCA method, based on Wuhan's road network. This analysis considers both the average walking speed of the total population and the varying walking speeds of different age groups. These results are then compared to highlight the differences in accessibility between these two approaches.

Third, based on the accessibility results, the equity of PGS access is evaluated using the Lorenz curve and the Gini coefficient. This step compares equity outcomes for the general population and specific groups with distinct walking speeds. Fourth, a walking speed sensitivity analysis is conducted to examine the effect of variations in walking speed ratios across different population groups. Since walking speeds can vary by country, region, and population due to ethnic, environmental, or cultural factors, the study explores how adjusting the speed ratios between disadvantaged groups and the general population impacts both accessibility and equity.

Finally, the accessibility and equity characteristics of PGSs in Wuhan are summarized, focusing on how neglecting walking speed differences among population groups may lead to biased equity results. The implications of these findings for urban planning and policy are also discussed.

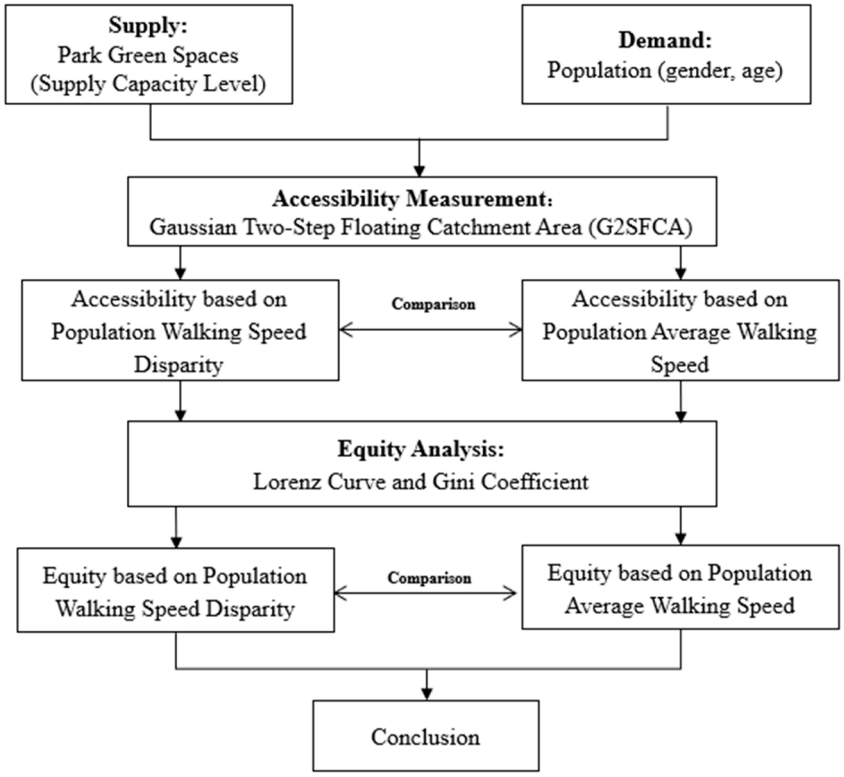


Figure 1. Research framework of measuring PGS accessibility and equity.

2.3. Data Sources and Processing

The data used in this study are divided into three categories: PGS, population characteristics, and walking commute data.

Spatial Data of PGSs: The PGSs included in this study refer to urban green spaces that offer free daily recreational activities to the public. Spatial locations for 744 PGSs across Wuhan were collected using the Baidu Map API location service (https://lbsyun.baidu.com/products/location, accessed on 7 February 2024). After verification through Baidu Street View and field investigations, 158 parks associated with institutions and enterprises, or those that charge fees or are not open to the public, were excluded, leaving 586 parks for analysis. The area of each park was measured using a combination of official data and remote sensing imagery. According to the Urban Green Space Planning Standards published by the Ministry of Housing and Urban-Rural Devevelopment in China [47], the supply capacity of a PGS is classified into five levels based on area, with each park's spatial location represented by its centroid.

- Level 1: 0.04–0.2 hectares.
- Level 2: 0.2–1 hectare.
- Level 3: 1–10 hectares.
- Level 4: 10–30 hectares.
- Level 5: Greater than 30 hectares.

Figure 2 shows the distribution of population and green spaces in Wuhan. Level 1 parks are the most common (144 parks), while Level 3 parks are the least common (34 parks). Approximately 57.8% of PGSs are concentrated in the main urban districts, reflecting a relatively better supply capacity in these areas. In suburban districts, PGSs are primarily located in areas with higher population densities.

Population Data: The population data for this study were sourced from the WorldPop 2020 population grid dataset (https://www.worldpop.org/), which offers high-resolution demographic information using advanced methodologies. This dataset employs machine learning techniques to integrate multiple data sources, including built-up area maps, night-

time light intensity, and census data, to disaggregate populations by age and gender into approximately 100 m × 100 m grid cells. Each cell contains detailed demographic estimates grouped in 5-year age intervals, enabling a fine-grained spatial analysis of population distribution. The WorldPop dataset is recognized for its accuracy and versatility, particularly in spatial population studies, where localized demographic patterns are essential for planning and policy. Previous studies [48,49] have extensively validated its reliability, making it a preferred choice for urban accessibility and equity research.

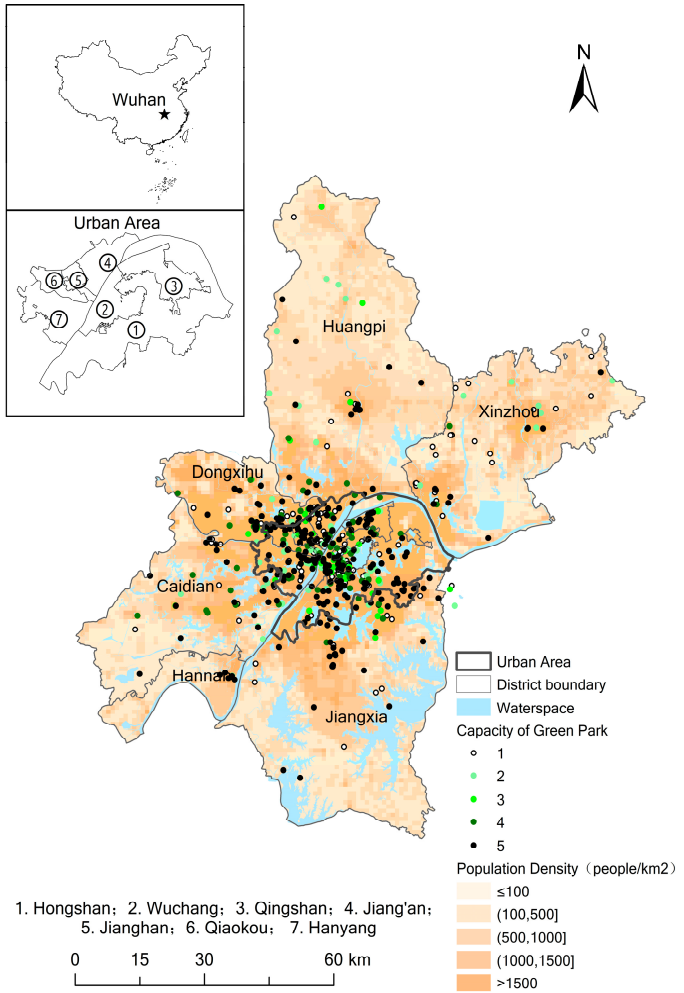


Figure 2. Study area and population density in Wuhan.

For this study, Wuhan was divided into 8936 1 km × 1 km grids to align with the city's administrative and spatial planning framework. Population characteristics for each grid were computed by summing the values from overlapping WorldPop grids, ensuring a comprehensive representation of demographic distribution at the local level. To model service accessibility, the geometric center of each 1km grid was designated as the demand point, serving as a proxy for the location of population activity and mobility. This approach allows for the integration of spatial population data with accessibility models while maintaining computational efficiency and scalability.

Figure 2 indicates that most areas within the main urban districts have a population density greater than 1500 people per square kilometer. Among these districts, Hongshan has the largest population, exceeding 2.95 million residents. In the six suburban districts, higher population density areas are primarily concentrated in the central parts of Dongxihu, the central region of Huangpi, the southern part of Xinzhou, the central region of Jiangxia, the northern part of Hannan, and the eastern part of Caidian.

Road Network and Walking Speed Data: Road network data were provided by the Wuhan Surveying and Mapping Institute (https://whkc.com.cn/). Walking speeds for different age groups were based on a study by Bohannon and Williams [50] (Table 1), which compiled data from over 40 studies on average walking speeds by age and gender worldwide. For this study, the population was divided into five age groups, in alignment with WorldPop data and the Wuhan Statistical Yearbook: 0–19 years, 20–34 years, 35–59 years, 60–79 years, and 80+ years. The 0–19, 60–79, and 80+ age groups are considered vulnerable groups, while the 20–34 and 35–59 age groups represent younger and middle-aged populations, respectively.

Table 1. Walking speeds of different age groups.

Age Group (Year)	0–19	20–34	35–59	60–79	Above 80
Speed (m/min)	71.94	81.12	82.74	71.94	57.24

Walking Speed Calculation:

Without considering walking speed differences, the average walking speed (S) for Wuhan residents was calculated using the following formula:

$$S = \sum_e \sum_g S_g * W_g \quad (1)$$

where S is the average walking speed in the study area, S_g is the walking speed for age group g, and W_g is the proportion of the total population represented by age group g.

When considering walking speed differences, the walking speed for each demand point i was calculated as

$$S_i = \sum_e \sum_g W_{ig} * S_g \quad (2)$$

where S_i represents the walking speed at the demand point, and W_{ig} is the proportion of the population in age group g within the area represented by demand point i.

2.4. Accessibility Measurement

The traditional 2SFCA method is used to measure the spatial accessibility of PGSs. This method first establishes a threshold distance or travel time for both supply and demand points, then performs a two-step search to compare the supply-to-demand ratio within the threshold range. However, a limitation of the traditional 2SFCA method is its reliance on a "binary cut-off" threshold, where areas either fully meet the threshold or do not meet it at all, without considering gradual changes in accessibility beyond the threshold. To address this issue, scholars have proposed various enhancements, such as the G2SFCA method, which incorporates a Gaussian function to model the distance decay effect.

The G2SFCA method is employed in this study, considering both the average walking speed and the walking speed differences among population groups. The walking time thresholds used to calculate PGS accessibility are 10 min, 15 min, and 20 min. The attractiveness $M(d_{ij})$ between a demand point i and a supply point j is represented by the distance decay function in Formula (3):

$$M(d_{ij}) \begin{cases} \dfrac{e^{(-\frac{1}{2})} \times \left(\frac{d_{kj}}{d_0}\right)^2 - e^{(-\frac{1}{2})}}{1 - e^{-(\frac{1}{2})}} & if\ d_0 \le d_{ij} \\ 0 & if\ d_{ij} > d_0 \end{cases} \quad (3)$$

where $M(d_{ij})$ is the distance decay function and d_0 is the threshold value for commuting cost. If the walking time from demand point i to PGS j is within the threshold value d_0, the attraction from supply point j to demand point i is reduced according to a Gaussian function. If the walking time exceeds d_0, the attraction is considered zero. Based on the distance decay function $M(d_{ij})$, the G2SFCA method involves the following two steps:

Step 1: Using j as the PGS centre, the method searches for all demand points i within the threshold range. The population at each demand point within the search area is summed, with population figures adjusted by the $M(d_{ij})$ function. The supply-to-demand ratio R_j for PGS j is then calculated using Formula (4):

$$R_j = \frac{S_j}{\sum_{i\in\{d_{ij}\le d_1\}} D_i * M(d_{ij})} \tag{4}$$

where R_j represents the supply-to-demand ratio of PGS location j, S_j is the supply capacity of the location j, and D_i represents the demand population at point i.

Step 2: Using each demand point k as the centre, the method searches for all PGSs j within the threshold range. The supply-to-demand ratios R_j for all PGSs are weighted by the distance decay function $M(d_{ij})$, and the results are summed to obtain the accessibility index A_k for each demand point k. A higher A_k value indicates higher accessibility. The formula is shown as follows:

$$A_k = \sum_{\in k\in\{d_{kj}\le d_1\}} R_j * M\left(d_{kj}\right) \tag{5}$$

The weighted accessibility WA_g for age group g at demand point k is calculated using Formula (6):

$$WA_g = \frac{A_k * N_{kg}}{T_g} \tag{6}$$

where N_{kg} is the number of people of age group g within the demand point k, and T_g is the total population of age group g in the study area.

2.5. Equity Evaluation Method

Based on the spatial accessibility of PGSs, this study further analyzes the equity of PGS distribution using the Lorenz curve and the Gini coefficient. Originally developed to analyze disparities in income distribution, the Lorenz curve and the Gini coefficient are now widely applied in studies of PGS accessibility equity, helping to identify and quantify the unequal distribution of green space resources across different communities.

In the context of PGS accessibility, the Lorenz curve plots the cumulative proportion of the population on the horizontal axis against the cumulative proportion of PGS accessibility on the vertical axis, illustrating the equity of public green space distribution. The Lorenz curve typically forms a downward-bending shape, where the closer the curve is to a straight diagonal line, the greater the equity in distribution; conversely, the closer it is to the axes, the more unequal the distribution of PGSs. The Gini coefficient is a statistical measure of inequality, with values ranging from 0 to 1. A Gini coefficient of 0 represents complete equity, while a coefficient of 1 indicates maximum inequality. The formula for the Gini coefficient is shown in Equation (7):

$$G = 1 - \sum_{i=1}^{n} (X_i - X_{i-1})(Y_i + Y_{i-1}) \tag{7}$$

where G is the Gini coefficient, n is the number of residential areas, X_i is the cumulative proportion of the population in the i-th residential area, and Y_i is the cumulative proportion of PGS accessibility value in the i-th residential area. For the first area when $i = 1$, both X_{i-1} and Y_{i-1} are zero.

3. Results

3.1. Spatial Analysis of Walking Speeds in Wuhan

The spatial distribution of population ratios for different age groups in Wuhan is shown in Figure 3, which uses the natural breaks method to classify population ratios into five categories, revealing an uneven spatial distribution of population ratios across age groups. The areas with the highest proportion of residents aged 0–19 years are located

in Jiangxia and Xinzhou, while the northwest of the main urban area, as well as Hannan and Caidian, show the lowest proportions of this age group (Figure 3a). The proportion of the 20–34-year-old age group is highest in the southeast of the main urban area and in Jiangxia district, while Huangpi, Xinzhou, and Hannan show lower proportions (Figure 3b). Residents aged 35–59 are more concentrated in the northwest of the main urban area, as well as Hannan and Dongxihu, whereas lower proportions are found in the northwest of the main urban area and in Jiangxia district (Figure 3c). The population aged 60–79 years is more prevalent in the Huangpi and Qingshan districts, while lower proportions are seen in Hongshan, Jiangxia, and Dongxihu (Figure 3d). The oldest group, those aged 80 and above, is more concentrated in Huangpi and the central and northern parts of the main urban area, whereas Jiangxia, Dongxihu, and Xinzhou have lower proportions (Figure 3e). Overall, Huangpi and the northwest of the main urban area show higher levels of aging, with more than 20% of residents in some areas aged over 60, while Jiangxia district has a higher proportion of young residents.

If the variation in walking speeds across age groups are not considered, the walking speed of all Wuhan residents is 77.89 m/min. When accounting for differences in walking speeds across age groups, walking speeds show a remarkable difference in Wuhan, ranging from 75.20 to 78.55 m/min across the study area. In detail, the average walking speeds in each district of Wuhan are shown in Figure 4. It is easy to see that the walking speeds in the main urban areas are clearly higher than those in the suburban region. Qiaokou has the highest walking speed among all districts, reaching 78.51 m/min, while the lowest walking speed in the urban area is in Jianghan (78.13 m/min). In suburban areas, Dongxihu has the highest walking speed at 77.71 m/min, followed closely by Hannan at 77.7 m/min. The lowest walking speeds are found in Xinzhou and Huangpi, at 77.2 m/min and 77.21 m/min, respectively.

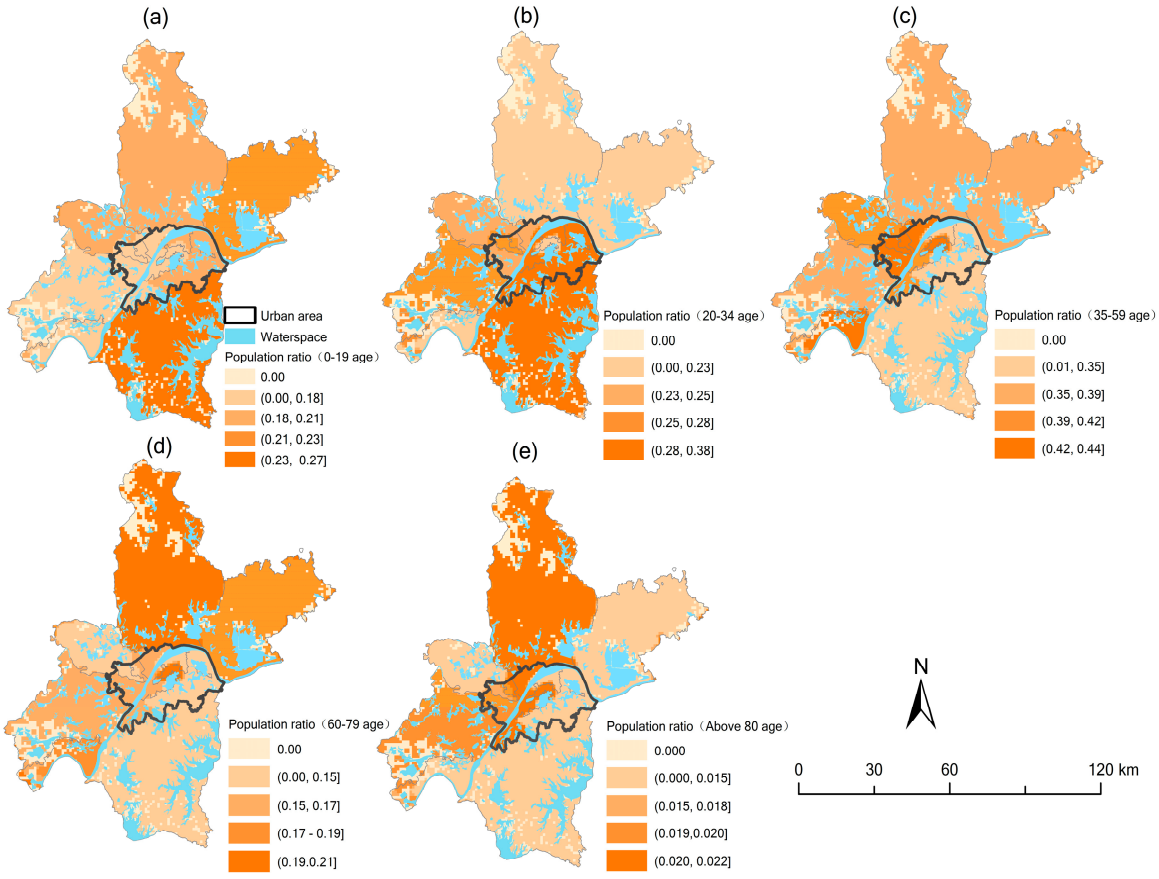


Figure 3. Population ratios of different age groups; (**a**) 0–19 age group; (**b**) 20–34 age group; (**c**) 35–59 age group; (**d**) 60–79 age group; (**e**) aged 80 and above.

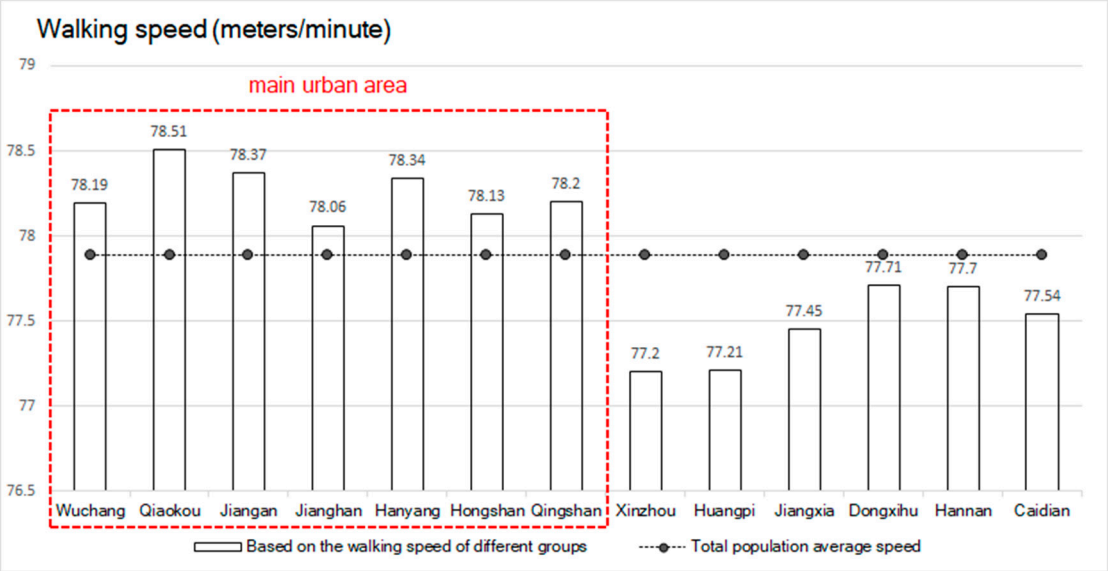


Figure 4. Average walking speeds in each district of Wuhan.

3.2. Park Green Space Accessibility Evaluation

The G2SFCA model was used to calculate the spatial distribution of PGS accessibility under different accessibility thresholds (10 min, 15 min, 20 min) based on both average walking speeds and walking speed differences. The accessibility scores are divided into five levels based on their distribution characteristics. An accessibility score of zero indicates that no PGS falls within the threshold range of a demand point, representing the worst accessibility. An accessibility score higher than 0.3 falls into the highest range, indicating the best accessibility at the demand point.

Table 2 shows that the accessibility results based on walking speed differences are significantly different from those based on average speed. Regardless of the threshold, considering walking speed differences increases the proportion of areas with an accessibility score of zero, reduces the average accessibility score, and decreases the level of dispersion. As the threshold increases from 10 min to 20 min, the average accessibility score increases significantly when walking speed differences are considered (from 0.027 to 0.128), while the standard deviation rises from 0.782 to 4.137, indicating an increase in dispersion. In contrast, the increase in average accessibility based on average walking speeds is smaller (from 0.207 to 0.228), and the standard deviation rises by only 0.176, indicating little change in dispersion.

Figure 5 shows the spatial distribution of accessibility scores under different threshold values, based on both average and group-specific walking speeds. When the threshold is set to 10 min, only 0.8% of areas (primarily concentrated near the central urban area) fall within the threshold range when considering walking speed differences (Figure 5a), compared to 5.3% when using average speeds (Figure 5b). As the threshold increases to 15 min, the proportion of areas within the threshold range rises to 1.5%; these areas are mostly concentrated around PGSs (Figure 5c). In contrast, 9.4% of areas fall within the threshold range when considering average speeds (Figure 5d); these areas are primarily within the Jiang'an, Jianghan, and Qiaokou districts. When the threshold is raised to 20 min, both scenarios see a significant increase in the proportion of areas within the threshold range, with accessibility in the main urban areas remaining superior to that in suburban areas (Figure 5e,f).

The weighted accessibility scores for different age groups are shown in Table 3. Regardless of the threshold range, the weighted accessibility scores for the 0–19 age group are lower than those for other groups, indicating poorer accessibility. When only average walking speeds are considered, the weighted accessibility score for residents aged 60 and above is higher than that for other groups. However, when considering differences in walking speeds, the accessibility score for residents aged 60 and above decreases relative to other groups.

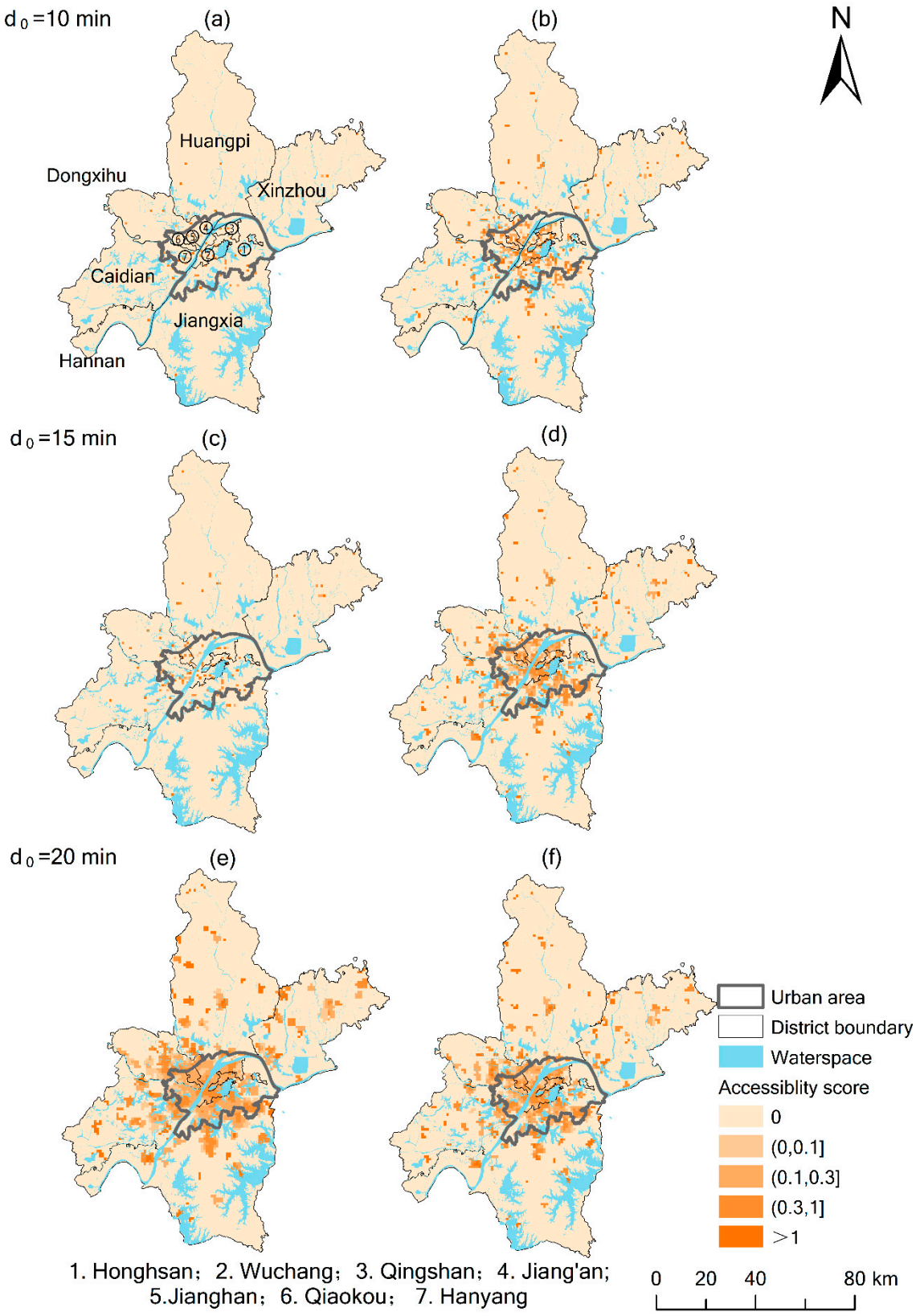


Figure 5. Accessibility scores of PGSs in Wuhan under different thresholds: (**a**) considering speed variation in age groups (d_0 = 10 min); (**b**) without considering speed variation in age groups (d_0 = 10 min); (**c**) considering speed variation in age groups (d_0 = 15 min); (**d**) without considering speed variation in age groups (d_0 = 15 min); (**e**) considering speed variation in age groups (d_0 = 20 min); (**f**) without considering speed variation in age groups (d_0 = 20 min).

Table 2. Characteristics of statistics of PGS accessibility scores.

Threshold	Whether Differences in Walking Speed Are Considered	Average	Median	Standard Deviation	The Proportion of Areas Outside Threshold
10 min	No	0.207	0.000	5.705	94.7%
	Yes	0.027	0.000	0.782	99.2%
15 min	No	0.227	0.000	5.767	90.6%
	Yes	0.075	0.000	2.073	98.5%
20 min	No	0.228	0.000	5.880	87.0%
	Yes	0.128	0.000	4.137	94.9%

Table 3. Weighted PGS accessibility scores for different age groups.

Threshold	Whether Differences in Walking Speed Are Considered	Ages 0–19	Ages 20–34	Ages 35–59	Ages 60–79	Ages Above 80
10 min	No	0.203	0.206	0.207	0.208	0.208
	Yes	0.024	0.028	0.027	0.028	0.027
15 min	No	0.224	0.207	0.207	0.209	0.208
	Yes	0.070	0.074	0.078	0.076	0.076
20 min	No	0.224	0.207	0.208	0.209	0.209
	Yes	0.125	0.128	0.129	0.128	0.128

3.3. Analysis of Park Green Space Equity

The results show that whether or not population walking speed differences are considered, there are notable differences in the Lorenz curves and Gini coefficients, which impact the evaluation of equity. Regardless of the threshold range, the Lorenz curves for accessibility based on walking speed differences are steeper than those based on average walking speeds (Figure 6). As the threshold increases, both curves flatten and move closer to the line of perfect equity.

When the threshold is set to 10 min, the Gini coefficient based on walking speed differences is 0.998, while the Gini coefficient based on average walking speeds is 0.992, indicating a 0.006 difference in equity. When the threshold increases to 15 min, the Gini coefficients for both scenarios decrease, indicating an improvement in equity. For instance, the Gini coefficient for walking speed differences decreases to 0.997, while the average speed scenario drops to 0.986. As the threshold increases to 20 min, the Gini coefficient for walking speed differences further declines to 0.996, while the average speed scenario drops to 0.979, showing a further increase in equity.

In summary, the Gini coefficients are consistently higher when based on walking speed differences, indicating lower equity. Additionally, the rate at which the Gini coefficient decreases with increasing thresholds is faster when based on average walking speeds. Table 4 shows that, regardless of the threshold, the Gini coefficient for all groups is 0.998 when walking speed differences are considered. However, when only average walking speeds are considered, the Gini coefficient for people under 20 is 0.993, while other age groups have a Gini coefficient of 0.992. This indicates that differences in accessibility equity between groups are more pronounced when only average speeds are considered.

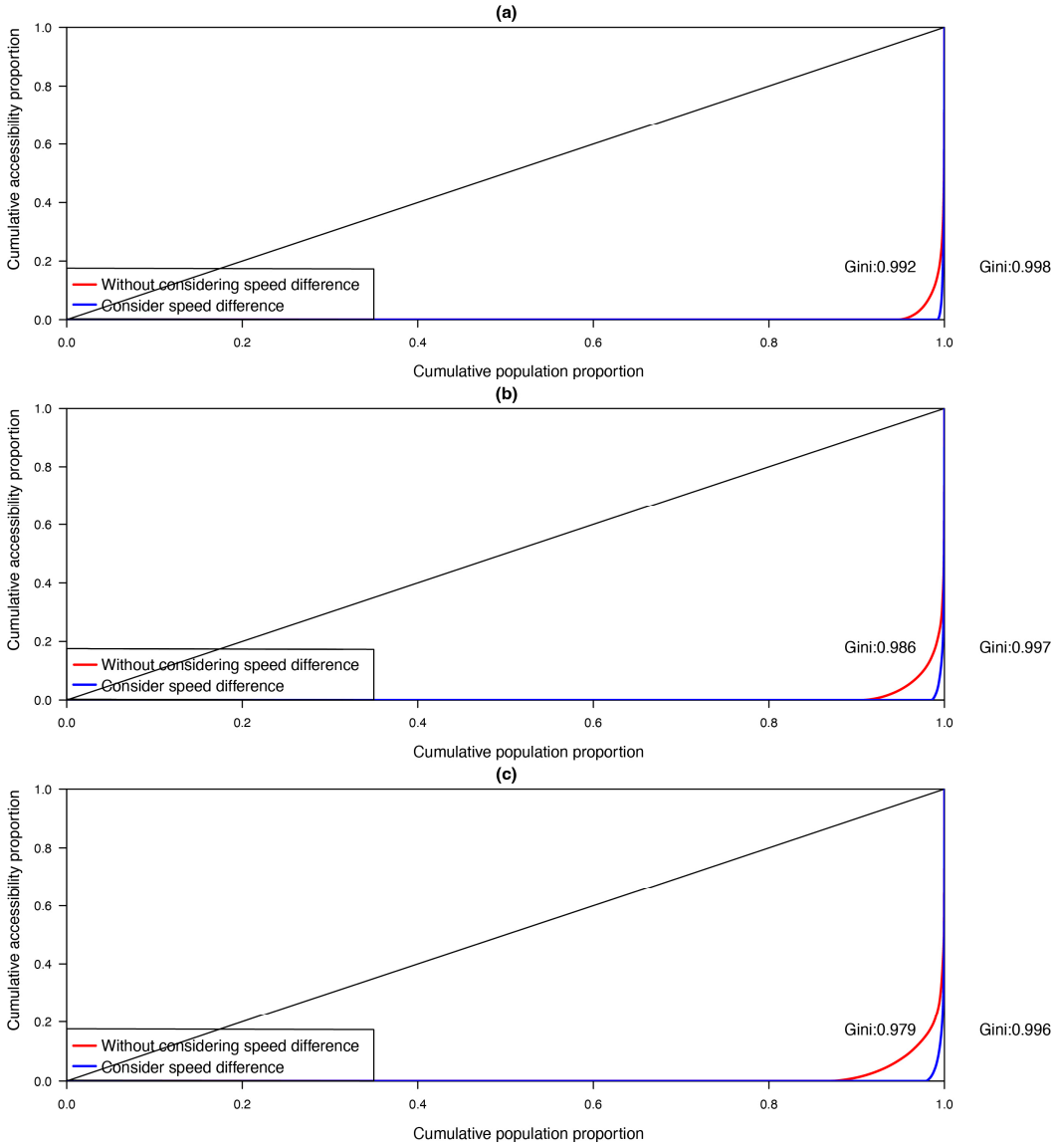


Figure 6. Lorenz curves and Gini coefficients of PGS accessibility: (**a**) 10 min threshold; (**b**) 15 min threshold; (**c**) 20 min threshold.

Table 4. Lorentz curves and Gini coefficients of PGS accessibility for different age groups.

Threshold	Whether Differences in Walking Speed Are Considered	Ages 0–19	Ages 20–34	Ages 35–59	Ages 60–79	Ages Above 80
10min	No	0.998	0.998	0.998	0.998	0.998
	Yes	0.993	0.992	0.992	0.992	0.992
15min	No	0.997	0.997	0.997	0.997	0.997
	Yes	0.988	0.986	0.985	0.986	0.986
20min	No	0.997	0.996	0.996	0.996	0.996
	Yes	0.982	0.978	0.979	0.981	0.980

3.4. Sensitivity Analysis of Walking Speeds

The walking speed data used in this study are based on universally applicable reference standards [50]. However, due to differences in ethnicity, geography, and other factors, the walking speed disparities between different age groups may not fully reflect the actual situation. Therefore, this section performs a sensitivity analysis by measuring PGS

accessibility and equity with a 15 min threshold by adjusting the walking speeds of the three vulnerable groups (under 20 years old, 60–79 years old, and over 80 years old) while keeping other population groups' speeds as constants. In scenarios 1–3, the walking speeds of the disadvantaged groups are reduced by 3% to 1%, respectively, while in scenarios 4–6, their speeds are increased by 1% to 3%. Table 5 shows the walking speeds for different population groups under these scenarios.

Table 5. Walking speeds for vulnerable groups in different scenarios (↑ means the ratio increase; ↓ means the ratio decrease).

Age Group	Referenced Speed	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
0–19 years	71.94	69.78 ↓3%	70.50 ↓2%	71.22 ↓1%	72.66 ↑1%	73.38 ↑2%	74.10 ↑3%
60–79 years	71.94	69.78 ↓3%	70.50 ↓2%	71.22 ↓1%	72.66 ↑1%	73.38 ↑2%	74.10 ↑3%
80+ years	57.06	55.35 ↓3%	55.92 ↓2%	56.49 ↓1%	57.63 ↑1%	58.20 ↑2%	58.77 ↑3%

Table 6 reveals minimal differences in the statistical characteristics of the accessibility scores (15 min threshold) and Gini coefficients across the different scenarios, with negligible changes in results. Specifically, the average accessibility score remains at 0.227 in scenarios 1–5 and increases slightly by 0.001 in scenario 6. The standard deviation of accessibility remains consistent at 5.88, except for a minor decrease in scenario 6. Similarly, the Gini coefficients show only slight variation, with the maximum value (0.892 in scenarios 1 and 2) differing from the minimum value (0.889 in scenario 6) by just 0.003, showing a small variation. Figure 7 demonstrates that the spatial distribution of PGS accessibility scores remains nearly identical across all scenarios, following a trend of decreasing accessibility from the central urban areas to the suburban districts. The proportion of areas with zero accessibility remains stable, with only a 0.2% difference between the maximum (95.0% in scenario 1) and the minimum (94.8% in scenario 6). This indicates that the variation in walking speed ratios across population groups has little effect on the accessibility and equity results, with the sensitivity of the model being relatively low.

Table 6. Accessibility and equity indexes of PGSs under different scenarios (with 15 min threshold).

Scenario	Average Accessibility	Median Accessibility	Standard Deviation of Accessibility	Gini Coefficient
Scenario 1	0.227	0.000	5.88	0.892
Scenario 2	0.027	0.000	5.88	0.892
Scenario 3	0.227	0.000	5.88	0.891
Scenario 4	0.227	0.000	5.88	0.891
Scenario 5	0.227	0.000	5.88	0.890
Scenario 6	0.228	0.000	5.87	0.889

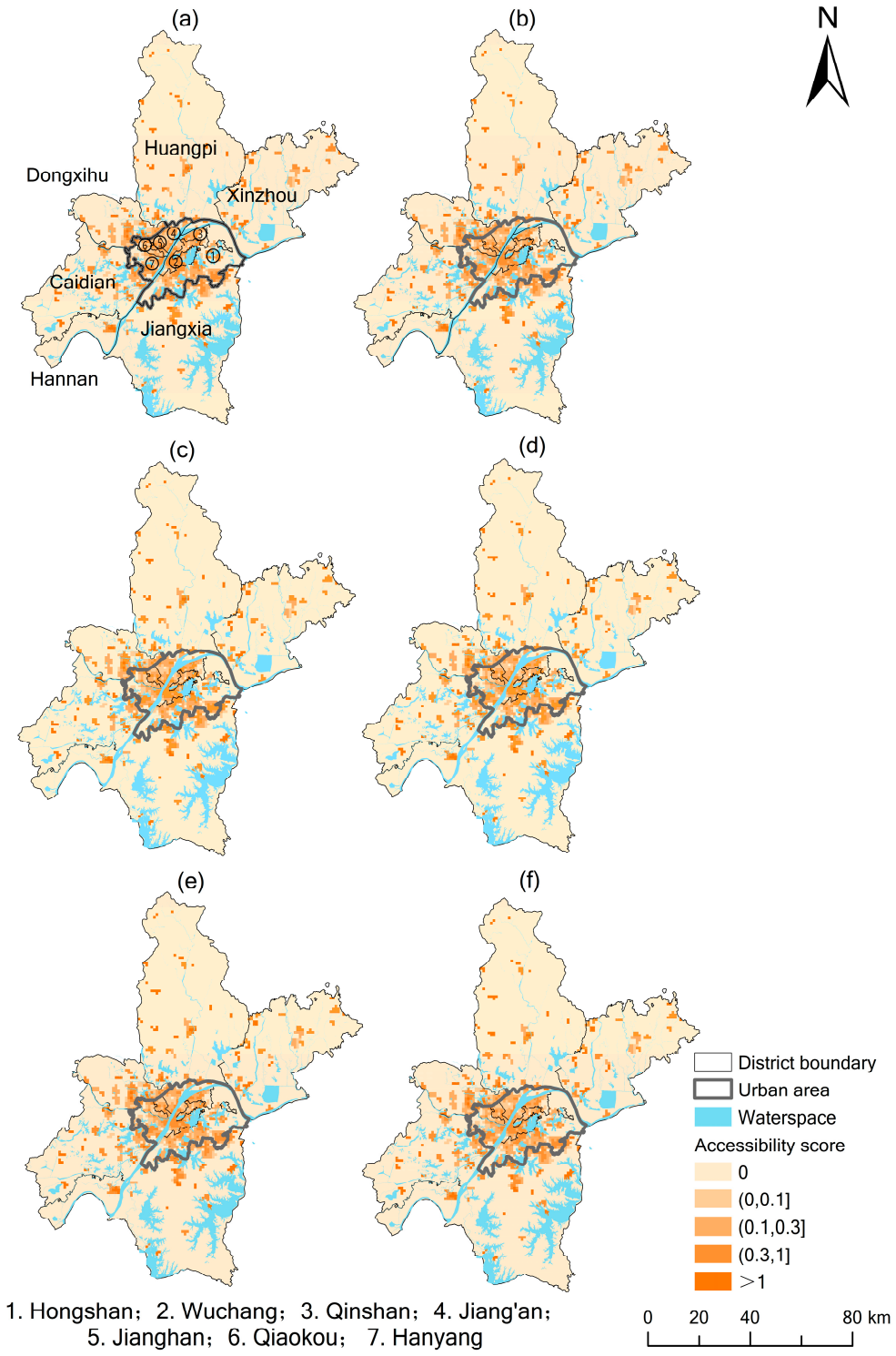


Figure 7. The spatial distribution of PGS accessibility under different scenarios (with 15 min threshold): (**a**) scenario 1; (**b**) scenario 2; (**c**) scenario 3; (**d**) scenario 4; (**e**) scenario 5; (**f**) scenario 6.

4. Discussion

This study assesses the spatial accessibility and equity of PGSs in Wuhan, accounting for differences in walking speeds across various population groups and the average walking speed. Some key insights have emerged from the results. First, it is obvious to see that there are significant spatial differences in walking speeds among residents in Wuhan. The walking speed of residents in the seven main urban districts is noticeably higher than in the

six outer districts. Then, if differences in walking speeds across various population groups are taken into account, the results for PGS accessibility and equity differ significantly. Moreover, spatial disparities in PGS accessibility are evident in Wuhan, regardless of whether walking speed variations in different age groups are considered. Central urban residents benefit from larger green spaces and a more extensive transportation network, giving them significantly better access than those in peripheral areas. Additionally, according to the sensitivity analysis, small variations in walking speed between vulnerable groups and others have a negligible effect on final outcomes. Within a certain range of walking speed ratios across vulnerable groups (−3% to 3%), the mean, standard deviation, and spatial distribution of PGS accessibility stay stable, showing minimal variation.

The remarkable spatial disparity in walking speeds is primarily due to the clustering and heterogeneous distribution of different age groups. For example, many universities and educational resources are concentrated in Hongshan, where the proportion of young people is high, resulting in the fastest walking speed in Wuhan. In contrast, Huangpi district has a higher proportion of elderly residents, leading to a slower walking speed compared to that in other areas. Meanwhile, this study finds that disregarding variations in walking speeds among different population groups can result in an overestimation of the accessibility and equity of PGSs. The primary reason is that using average walking speeds would overstate the walking speeds of vulnerable groups, such as the elderly and children. For instance, when accessibility is set to 15 min, the number of people in Huangpi with an accessibility score of 0 increases by 23%. This indicates that more people are unable to reach PGSs in areas with a high degree of aging when differences in walking speeds are taken into account (Figure 5b,c).

With the increasing trends of population aging and declining birth rates, the travel needs and habits of vulnerable groups, such as the elderly, will have a greater impact on urban planning and operations, especially in locating public services. If the variation in walking speeds among different groups is ignored when formulating public policies for public service resource allocation, it may result in these groups being unable to access public resources, such as PGSs, fairly. Furthermore, differences in walking speeds have significant implications for the siting and layout of other urban infrastructure. For example, the proper layout of public transit stations is crucial to the convenience of daily commuting. For elderly individuals with limited mobility and people with disabilities, transit stations that are too far away can directly affect their willingness to travel, reducing their opportunities to participate in social activities [51]. Similarly, the siting of hospitals, supermarkets, and other facilities should consider the walking capabilities of different groups to ensure that everyone can quickly access services in emergencies or meet their basic daily needs. Therefore, to achieve genuine urban equity and inclusiveness, urban planners need to pay more attention to the needs of vulnerable groups during the research and design process. This includes not only the elderly, but also children, pregnant women, people with disabilities, and other vulnerable populations. By adopting a more refined urban walking system plan and optimizing the siting and layout of public facilities, we can ensure that all residents have fair access to public services and resources, thereby improving the overall quality of urban life.

This study has several policy implications. First, regardless of whether variations in walking speed for different age groups are considered, the accessibility of PGSs in the main urban areas is far superior to that in suburban areas, which is consistent with some other studies [29,52]. Given their relatively low population density and more dispersed population distribution, suburban areas of large cities are more suited to the development of a greater number of small-scale parks and green spaces to improve accessibility. Second, future urban public service planning, including PGSs, should take into account differences in walking speeds across population groups, particularly for vulnerable groups. This aligns with the academic perspectives of many studies, suggesting that planning focused on vulnerable groups will become a key priority in future development [35,53]. Ensuring that public services are humanely and scientifically distributed will allow all groups, regardless

of mobility, to safely and conveniently access these services, ultimately improving societal well-being. Then, local government and planning sectors can use GIS and demographic mapping tools to continuously monitor and evaluate accessibility and equity in PGS distribution, enabling dynamic updates to policies as urban demographics evolve. Furthermore, future planning should involve local communities in the planning and decision-making process to better understand their needs and preferences for green spaces. Moreover, given that weighted accessibility for the 0–19 age group in Wuhan is the lowest among all age groups (refer to Table 3), the Wuhan government should prioritize improving accessibility for children and adolescents. This effort would promote park usage within this age group and enhance the overall equity index of PGS accessibility across all age groups.

Some future work can be carried out to improve this study. First, in evaluating the supply capacity of park green spaces, the current study classifies PGS supply levels based on the size of the parks, neglecting other factors that might influence the supply capacity, such as the completeness of infrastructure within the parks. Therefore, future research needs to refine the criteria for evaluating and classifying the supply capacity of PGSs. Second, the housing types, lifestyle habits, and commuting patterns of people in different areas are crucial factors for analyzing accessibility and optimizing the locations of PGSs, and should be a focus of future studies. For instance, residents living in high-rise buildings or central urban areas tend to be more reliant on PGSs. Third, the environmental and morphological characteristics of different parks can also influence walking behavior [33], such as strolling or jogging. Different age groups may have varying preferences when choosing PGSs; for example, teenagers may prefer parks with sports facilities, while older adults may favor flat, easy-to-walk, and accessible park areas. Future research should consider the impact of differences in park attractiveness on accessibility. Additionally, this study assumes the geometric center of the park green space as the park entrance, with access from all directions. In future research, the actual location of park entrances should be taken into account to measure accessibility more accurately.

5. Conclusions

PGS accessibility and equity are important elements for urban planning. This study aims to expand the literature by investigating whether ignoring age-related differences in walking speeds affects the measurement of PGS accessibility and equity. An empirical study was conducted in Wuhan, China. Some key findings emerged from the results. First, remarkable spatial disparities in walking speeds and PGS accessibility were observed, which is consistent with some previous findings. Central urban areas had better PGS accessibility compared to suburban areas due to more PGSs and more extensive transportation networks. Second, ignoring age-related walking speed differences led to an overestimation of accessibility and equity. Vulnerable groups, particularly the elderly and children, faced reduced accessibility when these differences were considered. Third, both Lorenz curves and Gini coefficients revealed greater inequities when walking speed differences were considered. While the main urban districts showed higher equity, suburban areas exhibited significant disparities, underscoring the need for targeted interventions. From the sensitivity analysis, it was found that variations in walking speeds had minimal impact on the overall accessibility and equity results, suggesting the robustness of the findings under different walking speed assumptions.

This study underscores the importance of incorporating demographic-specific mobility factors in urban planning. By acknowledging age-related mobility variations, urban planners can more accurately assess and address inequities in public service accessibility. These findings align with existing the literature on urban equity but extend its scope by emphasizing the mobility needs of aging populations, a critical issue in rapidly urbanizing and aging societies. Future research should refine park supply evaluation, incorporate demographic and behavioral data, and expand to diverse urban contexts for broader applicability.

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