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Accessibility Analysis of Urban Park Green Spaces in Nanning City Based on Network Analysis and G2SFCA

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Abstract

The accessibility of urban park green spaces holds significant importance for the daily lives of city dwellers and for evaluating urban liveability. This study integrates the Gaussian two-step floating catchment area method (G2SFCA) and network analysis to assess the accessibility distribution characteristics of park green spaces in Nanning City. The G2SFCA accounts for population density and park area to quantify per capita service capacity, while network analysis simulates real transport networks to evaluate distance-based and time-based accessibility. Results indicate significant disparities in accessibility across Nanning's districts: Qingxiu and Liangqing District exhibit the highest accessibility with average proportions of 65.84% and 45.54% respectively, while Xixiangtang and Xingning District record the lowest at 18.01% and 16.61%. Spatial Autocorrelation Analysis (Moran's I = 0.928) further indicates pronounced clustering, with high–high clusters concentrated in the southeast and low–low clusters in the northern and western areas. The comparative analysis highlights the methodological complementarity between supply–demand based and distance–cost based evaluations, providing a more robust understanding of green space accessibility. Policy recommendations suggest prioritising the addition of community parks and green corridors in low-accessibility and high-density areas such as northern Xixiangtang and western Jiangnan, while consolidating the "large core–small node" layout along the Yongjiang River. This research offers scientific support for ecological spatial planning and contributes to advancing the development of a liveable and sustainable urban environment in Nanning.

Keywords

Urban Park Green Spaces; Accessibility; Network Analysis; Gaussian Two-Step Floating Catchment Area Method (G2SFCA); Nanning City.

1. Introduction

With the acceleration of global urbanisation, urban green spaces play an increasingly prominent role in modern urban ecosystems, particularly in addressing climate change, mitigating the urban heat island effect, enhancing residents' quality of life, and promoting the transformation of urban landscape patterns [1-3]. Urban green spaces play numerous critical roles in temperature regulation and extreme climate mitigation, with individual characteristics influencing green space usage frequency and effectiveness [2]. Some scholars, utilising remote sensing and meteorological data, estimated the net primary productivity of parks in Beijing's central urban area over six consecutive years across multiple time phases, indicating a proportional relationship between increased green space area and carbon sequestration capacity [4]. whilst others have examined the psychological benefits of urban parks at the visual perception level [5]. However, most existing research has centered on the biophysical aspects of the "green space effect", with relatively limited exploration of spatial equity as a prerequisite condition for green space accessibility.

At the methodological level, Geographic Information System (GIS) technology has been extensively applied in park accessibility assessments, encompassing approaches such as the single park area index, ArcGIS network analysis, and Gaussian Two-Step Floating Catchment Area method(G2SFCA) [6-8]. The Gaussian Two-Step Floating Catchment Area method (G2SFCA) precisely calculates supply-demand matching relationships by integrating population density with park service capacity, revealing the ease with which residents access green space services [9]. Network analysis, meanwhile, simulates real transport networks to evaluate accessibility based on distance and time costs [10]. Nevertheless, existing research exhibits limitations including insufficient integration of subjective perceptions with spatial analysis, methodological constraints, and variations in approach applicability. For instance, while scholars innovatively incorporated visitor emotional factors to assess Suzhou's park accessibility through a blended subjective-objective approach, such methods remain underutilised in spatial analysis, and subjective data remains susceptible to noise and sample representativeness issues [11]. Another study employed GIS and Multi-Criteria Analysis (MCA) to predict green space suitability in Kigali, identifying population density as a key variable, yet failed to adequately account for the dynamic nature of transport networks [12]. Recent research exhibits a trend towards multi-source data integration, progressively combining spatial syntax, multi-modal transport analysis, and enhanced 3SFCA methodologies. Innovative studies have further integrated Dianping reviews and POI data to reveal disparities in social equity regarding park and green space access [13-14]. Others have validated the superiority of spatial syntax and multimodal transport analysis, demonstrating shortcomings in traditional methods regarding non-motorised accessibility, equity in new developments, and service matching for vulnerable groups [13].

Regarding park accessibility evaluation, network analysis provides shortest-path and reachability measurements grounded in actual transport networks, offering strong practical applicability. Its core advantage lies in precise calculations based on real transport infrastructure. However, network analysis often overlooks service-demand mismatches, failing to reflect equity disparities such as "one park serving many people" or "many people without green space". In recent years, researchers have progressively integrated subjective and objective evaluation frameworks into urban park accessibility analyses to broaden the explanatory power of traditional spatial methods. Scholars conducting optimised case studies in specific cities have revealed challenges in green space expansion during urbanisation, emphasising the critical role of green space layout assessments in addressing rapid urbanisation [15]. Nanning City in Guangxi, a model "Green City of China," explicitly stated in its November 2023 "Nanning National Ecological Civilisation Demonstration Zone Rules (2023–2030)" that urban development must be deeply integrated with ecological spatial planning, underscoring the importance of park accessibility research. Park accessibility significantly influences residents' health indicators and psychological behaviour, while directly correlating with urban liveability and social equity [16].

This study employs a coupled approach of the G2SFCA and network analysis (service area analysis, OD cost matrix) to construct a tripartite assessment framework integrating "demand-supply-spatial network". This achieves the following breakthroughs: Dual quantification of supply-demand matching and spatial barriers: G2SFCA quantifies "per capita green space services" through supply-demand ratios, while network analysis reveals geographical barrier effects via coverage distance and travel time; Methodological complementarity validation: By comparing outcomes from Gaussian Two-Step Floating Catchment Area method and network analysis, the study demonstrates distinct perspectives and complementary value in characterising green space service capacity; Policy orientation and technical applicability: Findings directly address governmental planning requirements, providing data support for optimising "large core-small node" green space layouts.

2. Model and Methodology

2.1. G2SFCA

Methodologically, the Gaussian Two-Step Floating Catchment Area method (G2SFCA) is a widely applied GIS analytical approach for assessing spatial accessibility to public service facilities. Its core principle integrates the traditional Two-Step Floating Catchment Area method(2SFCA) with a Gaussian distance decay model. Through two-stage supply-demand ratio calculations, it quantifies the spatial matching relationship between facility provision capacity and resident demand. Specifically, the conceptual framework of G2SFCA comprises two components:

At the supply location level, a service area with radius $D_0$is delineated centered on each supply point, forming a circular zone. The number of demanders within this zone is calculated for each demand point. Weighted and aggregated using the Gaussian distance decay function, this yields the total potential demand for the supply location. The supply capacity is then determined by dividing the area ratio of supply location j by the total potential demanders. The mathematical expression is:

$$R_j = \frac{S_j}{\sum_{k\in\{D_{ij}\le D_0\}} G(D_{ij}, D_0)P_k} \tag{1}$$

where S_j denotes the service capacity of supply location j, which in this study corresponds to the park area, representing the total park area available at supply location j. The denominator below represents the summation over demand points i at distances $D_{ij} \le D_0$from supply location j. P_k indicates the population size of demand point k, while$G(D_{ij}, D_0)$ denotes the Gaussian distance decay function, mathematically expressed as:

$$G(D_{ij}, D_0) = \begin{cases} \dfrac{e^{-\frac{1}{2}*\left(\frac{D_{ij}}{D_0}\right)} - e^{-\frac{1}{2}}}{1 - e^{-\frac{1}{2}}}, D_{ij} \le D_0 \\ 0,\ \ D_{ij} > D_0 \end{cases} \tag{2}$$

Step 2: Demand Area Level The spatial accessibility for demand area i is calculated using formula (3):

$$A_f^i = \sum_{l\in\{D_{il}\le D_0\}} G(D_{il}, D_0)R_l \tag{3}$$

where A_f^i denotes the spatial accessibility of demand location i, where a higher value indicates greater per capita accessibility to parks for residents of that location. D_{il} represents the distance between demand point i and supply location center l, while R_l is the supply-demand ratio of supply location l. centered on each residential location i, delineate a capture zone with radiusD_0. Identify all park green spaces l within this range. For each park green space l, compute the Gaussian distance decay function based on its distance D_{il} from residential location i. Overlay the supply-demand ratio R_i for each park green space to calculate the overall accessibility level for that residential location [17-18].

2.2. Network Analysis-Service Area Method

The service area analysis method determines the geographical coverage achievable by park green spaces under specified temporal conditions based on network topology. Its core principle simulates residents' accessible pathways to park facilities within the road network, encompassing all traversable edges, with results presented as service areas. The network dataset employed in this study accounts for turning restrictions, with directional choice set towards park facilities. Specifically, the analysis simulates residents walking from various locations to park facilities. Within the service area analysis, resistance thresholds were categorized into three levels: 1000 meters, 2000 meters, and 5000 meters. Assuming an average walking speed of 5 kilometers per hour. These thresholds correspond to walking durations of 12 minutes, 24 minutes, and 1 hour respectively. The analysis was conducted by applying a network traversal algorithm to each park. This involved evaluating paths originating from each park and traversing each node along the network topology. When the cumulative distance cost exceeded the predefined service area cutoff value, the search along that direction ceased. The algorithm then proceeded to evaluate other directions until all possible paths were assessed. The final service area analysis results were presented as polygons, delineating all edges within the network that satisfied the criteria. These edges collectively defined the service area boundaries for the park facilities.

2.3. Network Analysis-Origin-Destination (OD) Cost Matrix Method

The OD Cost Matrix method quantifies the shortest time cost from any origin (residential area) to target park green spaces within the study area, calculating the time cost from all origins to specified destinations. By computing cost values between different origin-destination pairs, it forms a matrix reflecting the time cost between starting points (residential areas) and terminating points (park green spaces). Compared to service area analysis within network analysis, the OD cost matrix method requires explicit lists of origins and destinations, focusing more on point-to-point cost aggregation. The calculation process comprises the following two steps:

Step One: Establish a new network and set the network travel cost as time. Calculate the time cost (Time, unit: minutes) based on the length (Length, unit: meters) of road segments using Formula (4):

$$Time = Length/83 \tag{4}$$

Step 2: For each origin, traverse the network to compute the shortest path to all destinations. Record the cumulative cost (e.g., total time, total distance) for each path, generating an origin-destination (OD) matrix report. Subsequently, aggregate the OD matrix report by time based on origin-destination information and join it to the settlement attribute table. Finally, the results of the OD cost matrix analysis are presented as a raster with interpolated settlement accessibility times, indicating areas within the region that meet the travel time criteria.

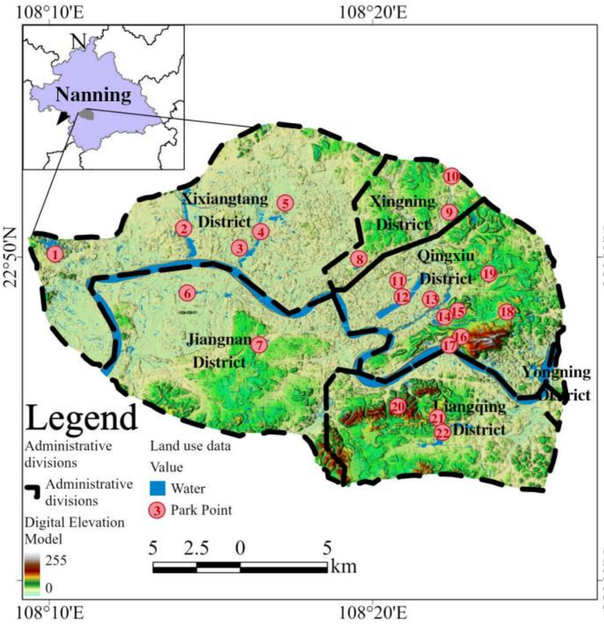
3. Data Sources and Preprocessing

3.1. Study Area Overview

The study area encompasses the central urban zone of Nanning City, Guangxi Zhuang Autonomous Region, bounded by the ring expressway (Figure 1), with a total area of approximately 405.98 km^2. The existing parkland and green spaces within Nanning's urban area cover roughly 41.15 km^2, accounting for approximately 10.136% of the total study area. By administrative district: Yongning District: 0.02% Xingning District: 6.24% Jiangnan District: 13.10% Xixiangtang District: 21.01% Qingxiu District: 26.98% Liangqing District: 32.42% Large, concentrated areas of parkland are primarily distributed in Liangqing District and Qingxiu District, while fragmented, scattered parkland is mainly found in Xixiangtang District, Xingning District, and Jiangnan District.

The overall distribution of park green spaces within the study area unfolds along water systems, forming a ribbon-like pattern centered on the Yongjiang River. Qingxiu Mountain and

Wuxiangling Forest Park serve as major core areas, with other parks functioning as minor cores, collectively situated in the central and southeastern parts of Nanning's urban district. Regarding the formation conditions of parks, Nanning's urban parks exhibit significant dependence on natural conditions. They were constructed alongside the Yongjiang River watercourse and utilised topographical features such as Qingxiu Mountain and Wuxiangling, relying on vegetation cover to establish park facilities.



Code	Park	District
1	Jinsha Lake Park	Xixiangtang
2	Xiangsi Lake Park	
3	Nanning zoo	
4	Mingyue Lake Park	
5	Flower Nursery Park	
6	Fengchao Lake Park	
7	Jiangnan Park	Jiangnan
8	People's Park	
9	Medicinal Botanical Garden	
10	Nakao River Wetland Park	
11	Jinhuacha Park	Qingxiu
12	Nanhu Park	
13	Mingehu Park	
14	Qingxiuhu Park	
15	Shimen Forest Park	
16	Qingxiu Mountain Scenic Area	
17	Yongjiang Waterfront Park	
18	Lining Sport Park	
19	Fengling Children's Park	
20	Wuxiangling Forest Park	Liangqing
21	Wuxiang Central Park	
22	Wuxiang Lake Park	

Figure 1. Current distribution of park green spaces in Nanning's central urban area (2024)

Table 1. Data Sources

Data Type	Data Source and URL
Settlement Data	Extracted via API service calls from AutoNavi Maps and Baidu Maps. https://lbs.amap.com/?ref=https://console.amap.com/dev/key/app
Green Space Boundary Data	Downloaded from the OpenStreetMap platform by delineating the study area: https://www.openstreetmap.org/
Road Network Data	Downloaded from the OpenStreetMap platform by defining the study area: https://www.openstreetmap.org/

3.2. Data Processing

First, the global 1km population raster data from was cropped (based on the Nanning Ring Expressway boundary) and resampled using a cubic convolution method (40 m resolution). Raster values were then corrected using a zonal normalisation approach combined with 2023 street-level statistical population data. The processed grid population values were linked to settlement POI data extracted via the AutoNavi Map API to serve as demand point weights (Pk). Green space data sourced from OpenStreetMap underwent topological checks (removing overlaps/gaps), conversion to vector polygons, and area calculation (Sj). Street-side green spaces <0.1ha were excluded. Geometric centers were extracted and overlaid with Landsat 9 imagery for manual verification (e.g., Qingxiu Hill's center point adjusted to main entrance). Nearest Neighbour Analysis (≤50m threshold) supplemented each park's closest road network connection point as a walking origin. The study area was divided into 40m × 40m grids (WGS_1984_UTM_49N projection). Population statistics within each grid were aggregated to generate a density raster (Figure 2). A 1000m radius neighbourhood table for parks was established to calculate potential demand population for Gaussian method calculations (Formula 1). Subsequently, spatial join operations were employed to merge the attribute tables of park green space vector data with the feature attribute tables of grid cells, generating a spatially referenced table exported as an Excel file. Supply-demand ratios for each area were calculated using Equations (2) and (3). Based on this, results were imported into Geoscene Pro software for a second spatial join. During secondary analysis, the proximity table was re-utilised to generate the accessible range of park green spaces within 1000m of each grid cell, thereby recalculating the supply-demand ratio for each area. Finally, incorporating a Gaussian distance decay function, the supply-demand ratio was multiplied by the distance decay value to produce grid-based park facility accessibility raster data. Finally, the results were visualised using a symbolic system to present the spatial accessibility distribution of park green spaces.

4. Results of Park Accessibility Analysis in Nanning's Central Urban Area

4.1. Park Accessibility in Nanning's Central Urban Area: G2SFCA Method

In the G2SFCA analysis, accessibility can be interpreted as the per capita green space area, determined by population density and green space coverage. Figure 2 reveals that in 2024, the study area exhibited a spatial pattern where accessibility was high in the southeast and central regions, while it was low in the west and north. High-accessibility zones predominantly cluster in the Qingxiu and Wuxiang districts, interconnected via the Yongjiang River area to form two similarly sized clusters. These zones feature substantial green space surrounded by lower population density, hence their high accessibility ratings. Medium-accessibility zones primarily line the Yongjiang River, with additional concentrations in southwestern Liangqing District and central Xixiangtang District. Low accessibility zones are concentrated in the northern part of Xixiangtang District, the western part of Jiangnan District, and the central part of Xingning District. These areas possess smaller green spaces and higher surrounding population densities, contributing to their low accessibility ratings. When overlaying population density maps (Figure 1) and green space distribution maps (Figure 3) of the study area, regions with greater accessibility—such as the Wuxiang New District and the ASEAN Business District—exhibit lower population densities alongside substantial surrounding green spaces. Overall, when compared with the distribution map of Nanning's park green spaces, high accessibility zones radiate outward in concentric rings centered on green areas. Zones with lower population density and proximity to green spaces exhibit higher accessibility. Table 2 shows the proportion of different value zones within the study area: high and relatively high value zones collectively account for approximately 20.06%, while relatively low and low value zones together constitute 60.91%. Table 3 presents the average proportion of accessible park green spaces across administrative districts. Liangqing District recorded the highest proportion at 65.84%, followed by Qingxiu District at 45.54%, while Xingning District had the lowest at 16.62%. The global Moran's I index of 0.928 indicates significant spatial autocorrelation in park accessibility. Furthermore, Local Indicators of Spatial Association (LISA) clustering analysis employing four clustering modes examined the bivariate autocorrelation between park accessibility and population density in Nanning, with results presented in Figure 4.

Figure 4 indicates that high-high clusters predominantly occur in the central-eastern and southern parts of the study area. This region features sparse population density and convenient transport links, hosting major green spaces such as Qingxiu Mountain Scenic Area, Wuxiang Lake Park, Wuxiang Central Green Park, and Wuxiangling Forest Park. The ample supply of green parks effectively meets local residents' travel and recreational needs. Low-low clusters predominantly occur in the northern, north-eastern, and south-western parts of the study area. These zones exhibit higher population density alongside scarce or insufficient green space provision. Consequently, green space redevelopment and spatial planning should prioritise areas with low accessibility and high population density.

Table 2. Proportion of Park Green Spaces by Accessibility Value Range

Value Range	Value Range	Proportion (%)
High-value zone	0.092620 - 0.171617	11.01
Moderately High Value Zone	0.052367 - 0.092619	9.59
Medium range	0.028644 - 0.052366	18.49
Lower value zone	0.012016 - 0.028643	24.99
Low Value Zone	0.000002 - 0.012015	35.92

Table 3. Average accessibility of park green spaces across different administrative districts

Administrative District	Percentage (%)
Liangqing District	65.84
Qingxiu District	45.54
Jiangnan District	19.11
Xixiangtang District	18.02
Xingning District	16.62

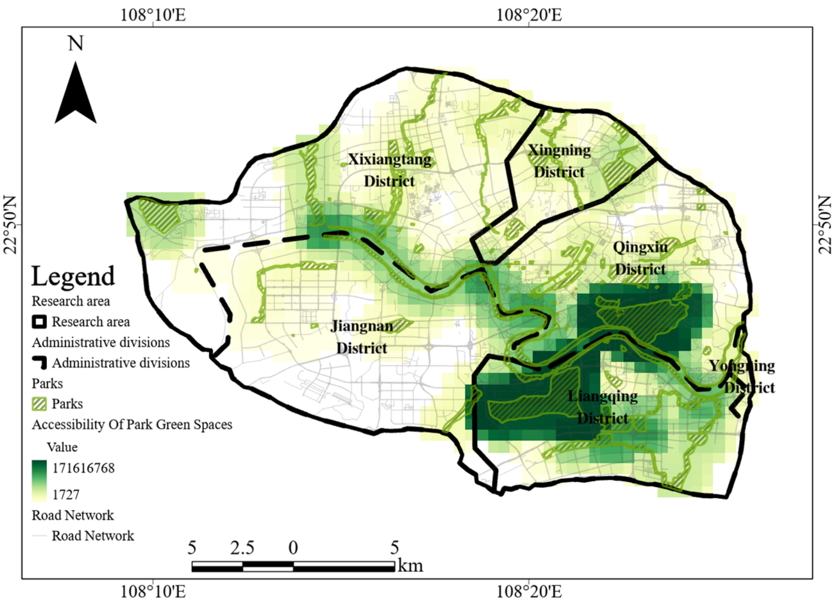


Figure 2. Accessibility analysis results for park green spaces in Nanning's central urban area based on the G2SFCA

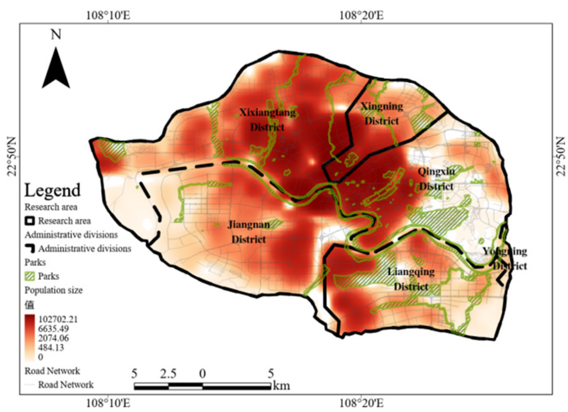


Figure 3. Population density distribution map of Nanning's central urban districts

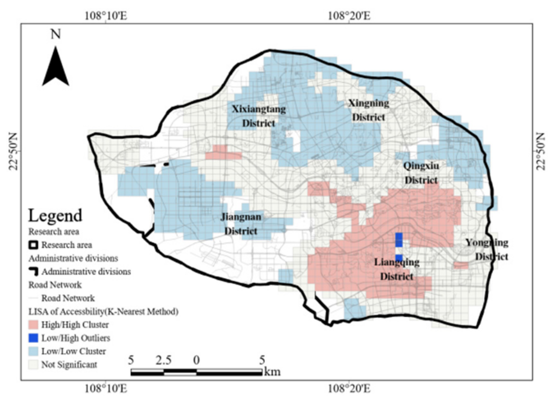


Figure 4. Results of cluster analysis

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4.2. Network-Based Accessibility Analysis of Parks in Nanning‘s Central Urban Area

4.2.1. Service Area Method

In service area analysis, accessibility may be conceptualised as the spatial distance from a given point within the study area to green spaces. The study area was divided into five discrete zones: 0–1000, 1000–2000, 2000–5000, and >5000 meters, corresponding to high, moderately high, medium, and low accessibility zones respectively. Figure 5 illustrates that in 2024, green space accessibility within the study area similarly exhibits an overall spatial pattern of high accessibility in the southeast and central regions, and low accessibility in the southwest and northwest. These high-accessibility zones are primarily distributed in the Qingxiu and Wuxiang districts. Within these areas, green spaces are either more dispersed or cover larger areas, resulting in generally extensive 1000-meter zones from points to green spaces, thus qualifying as high-accessibility zones. Medium accessibility zones primarily follow the Yongjiang River course, extending into the southwestern part of Liangqing District and the central area of Xixiangtang District. Low accessibility zones are concentrated in the northern part of Xixiangtang District, the western part of Jiangnan District, and the central part of Xingning District. These areas feature more clustered green spaces or smaller green areas, with larger zones within them having distances of 2000–5000 meters from any point to the nearest green space, thus constituting low-value zones. The average accessibility distance denotes the mean distance from any point within the area to the nearest green space. Table 4 presents the average accessibility distances across different administrative districts. A shorter average distance indicates either dispersed green space distribution or larger green areas. Liangqing District and Qingxiu District ranked first and second respectively, with average distances of 807.12 and 873.03 meters. Xingning District, exhibiting the lowest accessibility, recorded an average distance of 1732 meters.

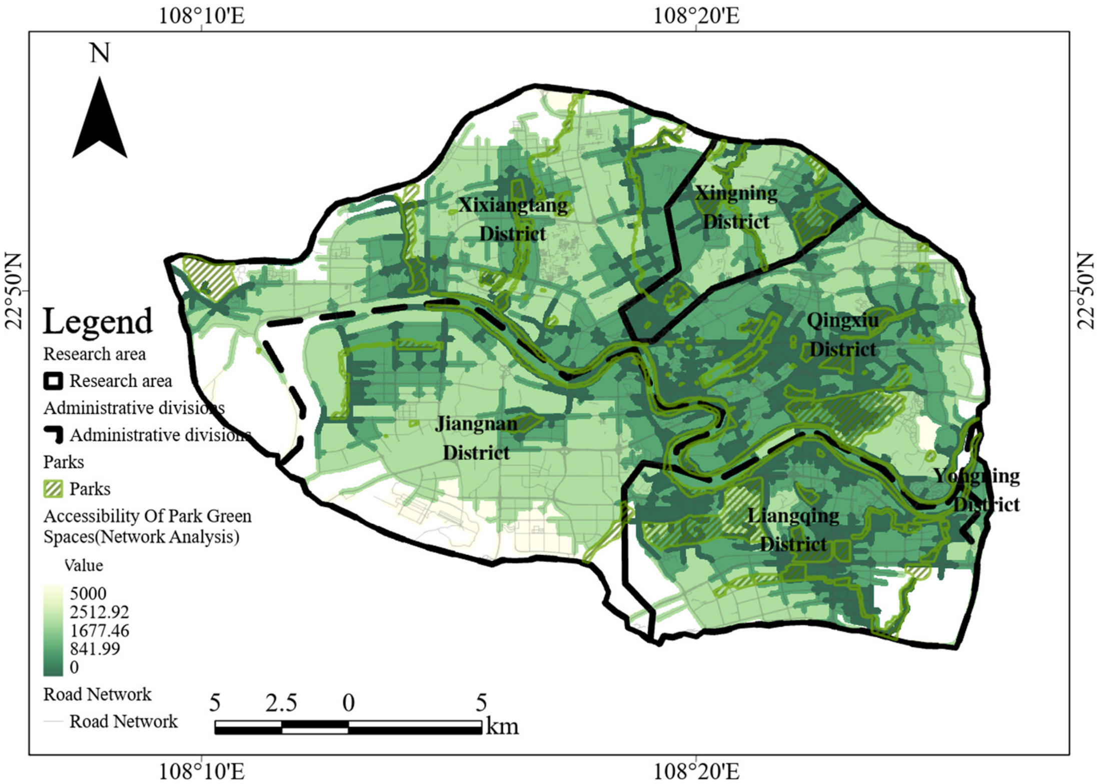

Figure 5. Accessibility of park green spaces in Nanning’s central urban area based on the network analysis (service area analysis)

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Table 4. Average accessible distance of park green spaces across administrative districts

Administrative District	Average Accessibility Distance to Park Green Spaces (m)
Liangqing District	807.12
Qingxiu District	873.03
Jiangnan District	956.32
Xixiangtang District	1364.04
Xingning District	1732.21

4.2.2. Origin – Destination Cost Matrix Method

Origin–Destination cost matrix analysis provides a more precise characterization of the spatial heterogeneity of green space accessibility compared to the service area analysis method. In this analysis, accessibility is defined as the minimum cost value along dynamic network paths. The study area's accessibility is divided into six discrete zones based on 30-minute intervals: high-value zones (accessibility within 1 hour), medium-value zones (1-2 hours), and low-value zones (2-3 hours). Figure 6 demonstrates that green space accessibility in the study area for 2024 exhibits characteristics consistent with the aforementioned methods: high accessibility zones predominantly occur in Qingxiu and Liangqing Districts, medium accessibility zones are distributed across Xingning and Xixiangtang Districts, while low accessibility zones are concentrated in Jiangnan District. Table 5 presents the median average accessibility times for park green spaces across different administrative districts. The average accessibility time denotes the duration required for residents to travel from the starting point (residential location) to the endpoint (park green space location) within the cost matrix. Qingxiu District and Liangqing District ranked first and second with 24 and 29 minutes respectively, while Xingning District and Xixiangtang District ranked third and fourth with 31 and 38 minutes. Jiangnan District ranked last with an average accessibility time of 70 minutes.

Table 5. Median average accessibility times to park green spaces by administrative district

Administrative District	Median Average Access Time to Park Green Spaces (minutes)
Qingxiu District	24
Liangqing District	29
Xingning District	31
Xixiangtang District	38
Jiangnan District	70

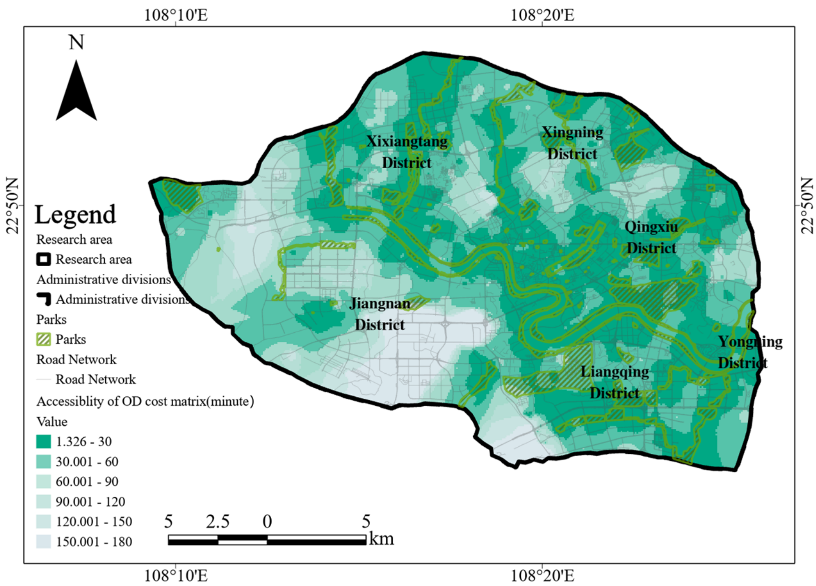

Figure 6. Accessibility of park green spaces in Nanning's Central Urban Area based on the network analysis (OD cost matrix)

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4.3. Comparison and Evaluation of the Three Accessibility Analyses

The three accessibility analyses collectively reveal the current accessibility of parks in Nanning. The spatial distribution of accessibility in Nanning is highly uneven, with disparities in both accessible park area and population coverage. Parks are primarily concentrated along both banks of the Yongjiang River, in Qingxiu District, the southern part of Liangqing District, and the northwestern part of Xixiangtang District. Other administrative districts feature only scattered parks. Among these, the Qingxiu area exhibits the best accessibility, with an average accessible distance of just 0.873 km. with 39.49% of the population residing within 0-1000m reachable zones and 36.59% within 1000-2000m zones. Liangqing District recorded an average reachable distance of 0.807km, with 44.11% of residents within 0-1000m zones and 32.12% within 1000-2000m zones. Xixiangtang District and Jiangnan District showed relatively poorer accessibility, while Xingning District recorded the lowest figures: only 20.15% of its area was within 0-1000m reachability, and 25.70% within 1000-2000m reachability. The combined reachability of these two ranges barely exceeded Qingxiu District's 0-1000m reachability figure (Table 6).

The distinctions between the three methodologies lie in: the Gaussian Two-Step Floating Catchment Area method incorporates population variables while simultaneously considering factors such as distance and park area, yielding conclusions that to some extent reflect per capita green space availability and accessibility. Conversely, service area analysis within network analysis cannot account for per capita metrics. relying solely on the variable of accessible distance. Network analysis employing the origin-destination cost matrix, however, calculates the shortest path and travel cost from each residential point to parks based on transport networks and population distribution data, generating a more precise spatial distribution map of accessibility. As research deepens, the limitations of single indicators become increasingly apparent. Therefore, these three methods should complement each other to provide a scientific description of accessibility in Nanning.

Table 6. Proportion of park green space accessibility by administrative district using network analysis methods

Administrative District	0–1000 m	1000–2000 m	2000–5000 m	>5000 m
Liangqing District	44.11%	32.12%	23.48%	0.29%
Qingxiu District	39.49%	36.59%	22.95%	0.07%
Jiangnan District	26.89%	24.29%	40.80%	8.02%
Xixiangtang District	23.79%	31.93%	42.25%	0.02%
Xingning District	20.15%	25.70%	47.63%	6.52%

5. Discussion

Compared to studies employing either network analysis or the Gaussian Two-Step Floating Catchment Area method (G2SFCA) alone [19-20], this study couples three methodologies, establishing for the first time a coupled model integrating the G2SFCA with two network analysis approaches. This achieves a dual quantitative assessment of supply-demand matching and spatial distance. By integrating population density and park area, the G2SFCA quantifies "green space services per capita", aligning more closely with residents' actual needs and significantly enhancing the comprehensiveness of accessibility assessment. Network analysis, focusing on spatial distance, intuitively reflects the impact of geographical barriers on accessibility (as demonstrated by Table 4 and Figure 2 data). The divergence between the two methods is particularly pronounced in Qingxiu District: Despite its high population density, Qingxiu District features large, concentrated green spaces like Wuxiangling Forest Park. Consequently, the Gaussian method indicates significantly higher accessibility (43.543) than the network method (average accessible distance: 873.03 meters), which relies solely on distance calculations. This higher weighting in the supply-demand ratio calculation (Formula (1)) highlights the critical role of green space area in matching supply and demand. Conversely, the northern part of Xixiangtang District, characterised by fragmented green spaces and dense population, was identified as a low-value area by both methods, confirming the necessity of methodological complementarity. This cross-validation offers a new paradigm for accessibility assessment in complex urban environments, overcoming the limitations of single-method approaches.

Compared to the methodology employed by some scholars in their research on 15-minute accessibility within cities based on POI data [21], this study more precisely captures micro-scale supply-demand relationships through grid-based population data and refined road network analysis. Unlike approaches combining subjective evaluations with visitor sentiment, this research focuses on objective spatial analysis, laying a quantitative foundation for subsequent studies integrating subjective and objective perspectives [11]. Methodologically, this study constructs a tripartite assessment framework integrating "demand - supply-spatial networks", transcending the limitations of traditional single-indicator approaches. Regionally, using the green city of Nanning as a case study, it reveals the distribution characteristics of urban green spaces shaped by the Yongjiang water system and mountainous topography, forming a "large core - small nodes" landscape pattern. This research fills a gap in green space planning studies for major cities in central and western China. The findings not only provide empirical support for the Nanning National Ecological Civilisation Demonstration Zone Plan but also offer reference for optimising green space systems in cities with similar topography (e.g., Guangzhou, Changsha).

Despite methodological innovations, this study exhibits two shortcomings: firstly, it fails to incorporate additional multi-source data (such as vegetation coverage, fractal dimension, edge density, and Baidu ratings), resulting in an incomplete assessment of park green space provision capacity; Secondly, it did not incorporate equity analysis (linking demand for urban green spaces to demographic characteristics such as gender, age, and income), overlooking how varying population groups' demand for parks, green vegetation coverage, and provision of recreational facilities influence accessibility [22-23]. Thirdly, it failed to account for the impact of alternative transport modes [24]. Future research may expand in the following directions: integrating multi-source data to assess park accessibility from perspectives of local microclimate, transport conditions, and equity [23], or placing greater emphasis on interdisciplinary collaboration. By combining Geographic Information Systems (GIS), remote sensing technology, and big data analysis, we can deepen our understanding of urban park accessibility and its societal impacts. Concurrently, as societal demands evolve and technological advancements progress, researchers should explore innovative methodologies and tools to address contemporary challenges, thereby advancing sustainable urban development and optimising the human living environment.

6. Conclusion

This study systematically assessed accessibility disparities in park green spaces within Nanning City by integrating spatial distribution characteristics with Gaussian Two-Step Floating Catchment Area method (G2SFCA) and network analysis techniques. Key findings are as follows:

Spatial Distribution Characteristics: Park green spaces in Nanning's central urban area exhibit a distribution pattern characterised by "riverine clustering, internal sparseness, and peripheral concentration". Green spaces along the Yongjiang River predominantly form continuous, ribbon-like distributions, creating two major core clusters in Qingxiu District and Liangqing District. Within the urban core, green spaces are fragmented and scattered, primarily consisting

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of small community parks. In contrast, the city's peripheral zones (such as Wuxiangling Forest Park) feature large-scale, concentrated distributions.

Accessibility disparities: Qingxiu and Liangqing Districts exhibit significantly superior accessibility compared to other areas due to concentrated large-scale green spaces and dense road networks. the Gaussian Two-Step Floating Catchment Area method indicates a supply-demand ratio of 65.84% in Qingxiu District and 45.54% in Liangqing District. Conversely, northern Xixiangtang District exhibits a ratio of merely 18.02% due to fragmented green spaces and high population density, while Xingning District registers an even lower figure of 16.62%. Network analysis further corroborates these findings: the average walking distance to green spaces for Qingxiu District residents is 873 meters (approximately 10 minutes), while Liangqing District residents walk 807 meters. In contrast, Xingning District residents face a distance of 1732 meters (approximately 20 minutes), revealing substantial disparities in spatio-temporal costs.

Methodological Complementarity: The Gaussian method highlights supply-demand mismatches by quantifying "per capita green space provision", while network analysis reveals geographical barrier effects through "coverage distance" and "travel time". Cross-validation indicates Qingxiu District excels in both approaches due to "economies of scale" and an efficient road network, whereas northern Xixiangtang District is jointly identified as a low-value area owing to "population-resource" misalignment.

This study provides scientific grounds for Nanning's park and green space planning: it recommends prioritising the addition of community parks and green corridors in low-value areas such as northern Xixiangtang District and western Jiangnan District, while extending the "core-node" network along the Yongjiang River system. Future research may further integrate multi-source data (e.g., green space quality, multi-modal transport) and incorporate social equity analysis to deepen understanding of the synergistic mechanism between spatial equity and social equity, thereby advancing the sustainable development of urban ecology and the human living environment.

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