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Exploring Discrepancies Between Perceived Accessibility and Spatial Accessibility Modelling: a Case Study of Urban Parks in Guangzhou, China

Abstract:

Despite global initiatives to improve access to urban green spaces (UGS) in line with the United Nation's Sustainable Development Goals, it remains a challenge to accurately measure the spatial accessibility of UGS. Traditional measurements often fail to match residents' perceptions of accessibility, highlighting a gap between objective measurements and subjective experiences. This study explored the Spatial Modelling Accessibility (SMA) results of parks derived from various approaches, while also examining the differences with Population Perceived Accessibility (PPA).

Our results reveal significant inconsistencies, with over 70% of accessibility measurements differing between spatial analyses and residents' perceptions. Exploring spatial distribution features within identical regions under different SMA for parks confirms the regional stability of the accessibility modelling process. By assessing a diverse array of SMA approaches, this study identifies methods that best reflect PPA. SMA approaches incorporating population preferences and socio-demographic factors offer a more refined understanding, often aligning more closely with PPA. Particularly, models adjusted for travel time and demographic preferences better capture residents' perceptions of accessibility. Integration of population preferences addresses the challenge of defining service radii, a known limitation of traditional models.

The study highlights the important choice of the SMA approaches and highlights the need to integrate socio-demographic considerations to refine the assessment of UGS accessibility. It contributes to more accurate and inclusive urban planning strategies.

Keywords: Urban Green Space provision; Spatial Accessibility; Perceived Accessibility; Modelling Methods; Socio-demographic Factors; Green Equality

1.Introduction

In the context of climate change and urban expansion, urban green spaces (UGS) have emerged as critical refuges for city residents, providing a range of environmental and cultural benefits that significantly enhance well-being. UGS serve not only as natural environments for leisure activities, but also as places for social interactions that support mental and physical health and contribute to a sense of belonging (Bedimo-Rung et al., 2005; Cohen et al., 2007; Peters et al., 2010; Ekkel & de Vries, 2017; Ferguson et al., 2018). Recognising their importance, the United Nations has championed the goal of universal access to safe and inclusive green spaces as part of its Sustainable Development Goals (United Nations, 2015), sparking a global initiative to improve accessibility to UGS. This commitment demonstrates that the accessibility of UGS is a critical component to be considered in urban policy and planning.

UGS accessibility, however, is a multidimensional concept, shaped by a web of factors including land use, transport systems, and individual preferences and constraints, making it difficult to assess (Miller, 2018). Accessibility encompasses more than just physical proximity; it also includes the ease with which different segments of the population can reach and use these spaces. This broader understanding of accessibility is directly linked to broader goals of social equity and environmental justice, but there are many challenges. Despite varied methodologies, the consensus among scholars is the reliance on Geographical Information Science (GIS) technology for comprehensive accessibility assessments. Traditional measures of accessibility are obtained through spatial modelling accessibility (SMA)， which usually focus on spatial characteristics such as distance or travel time, neglecting the subjective perceptions of urban residents. These population perceived accessibility (PPA) approaches often differ from objective spatial measures, highlighting the complex influence of personal preferences, social and demographic factors on how accessibility is experienced.

Recent research highlights the variability in accessibility measurement methods, which can affect the results of SMA analysis (Budd & Mumford, 2006; Mears and Brindley, 2009). In addition, the discrepancies between SMA and PPA also indicate socio-demographic factors such as age, gender, income and mobility play a critical role in shaping perceptions of accessibility, challenging the adequacy of a single approach to measuring UGS accessibility (Phillips et al., 2023; El Murr, Boisjoly, & Waygood, 2023; Ma, Brindley, & Lange, 2022a, 2022b; Ode Sang et al., 2016; Yang et al., 2022).

To address these research gaps, our study focuses on exploring the discrepancies between PPA and different approaches to modelling SMA, using Guangzhou, one of China's largest cities as our research context. By integrating modelling methods and survey data, this study aims to answer three research questions: (1) How do different spatial modelling approaches affect UGS accessibility outputs?; (2) How do these different outputs vary in their spatial distributions?; and (3) Which spatial modelling approaches generate output that best reflects PPA?

Our study focuses on the critical role of method selection in SMA modelling for UGS planning, recommending performing scenario-specific analyses that consider local traffic conditions and population density by integrating demographic data and preference weights, avoiding over-generalisation. It offers a guidance the strategic development of UGS. It is expected to refine the accessibility of urban planning and design strategies to better match the perceived needs and preferences of urban residents' UGS.

The remainder of this paper is organised as follows: Section 2 presents a literature review on the various methods used to measure and compare both SMA and PPA, and the influence of socio-demographic characteristics on these measures. Section 3 details the methodology and data used in our study, while Section 4 analyses the results and discussion. Finally, Section 5 outlines the main conclusions and implications for urban planning and design.

2.Literature Review

Accessibility is widely used in urban planning, transport studies and related fields and encompass both spatial proximity and perceived ease of access, highlighting the need for a comprehensive approach to assessment (Parks, 2004; Wang, 2012; Geurs & Van Wee, 2004). SMA includes not only physical distance or travel time, but also factors such as transport capacity, distribution of destinations, individual characteristics and quality of destinations. PPA examines a person's perception of the accessibility of a particular mode of transport and can be refined to assess an individual's perception of different transport systems (Lattman, Olsson & Friman, 2018). Moseley (1978) identifies the core elements of accessibility as the people, the activities and services they demand, and the connectivity facilitating these interactions. This framework helps urban planners in evaluating facility access by incorporating serviceability, population demand, and transportation connectivity.

In the field of urban planning and public health, the ability to access UGSs within reasonable distances has emerged as a key factor influencing both physical and psychological well-being. An existing body of research highlights the diverse benefits derived from the proximity and ease of access to parks and green areas, which contribute to healthier lifestyles and overall well-being (Manandhar, Suksaroj & Rattanapan, 2019; Datzmann et al., 2018; Ghimire et al., 2017). Moreover, Wang, Brown, and Liu (2015) have expanded the understanding of park accessibility, positing it as a multi-dimensional metric that reflects the willingness of individuals to invest time, effort, and financial resources in interacting with green spaces beyond mere physical proximity.

Planners and local governments are increasingly recognizing the importance of UGS accessibility. This understanding aligns with the concept of the "X-minute city," which aims to enhance community development by ensuring that essential services and amenities are within a short walk or bike ride from home (C40 Cities, 2020). Many countries also advocate similar concepts, such as '20-minute neighbourhoods' in Oregon (Steuteville, 2008); the "15-minute community-life circle" in China (Weng et al., 2019; Li, Zheng & Zhang, 2019); the principle that the public should be able to access green spaces or bodies of water, such as woodlands, wetlands, parks, and rivers, within a 15-minute walk from home in England (Natural England, 2023); and a 15-minute walking distance from the nearest UGS for residents in Europe (Stanners and Bourdeau, 1995).

Geurs and Van Wee (2004) categorized accessibility measurements into four perspectives: infrastructure-based, individual-based, location-based, and utility-based. Various methods have been proposed and applied to measure accessibility within urban contexts, each presenting advantages and limitations (Dai, 2011; Dony et al., 2015; Li et al., 2021; Stessens, 2017; van Herzele & Wiedemann, 2003; Zlender & Ward Thompson, 2017). However, a single SMA measure often falls to fully capture the service state of UGSs, prompting a shift towards a blend of algorithmic models and spatial processing techniques for a comprehensive assessment of the accessibility of parks. (Liu, Remme et al., 2020).

Location-based measures for assessing accessibility are broadly categorized into three types: distance measures, cumulative opportunities, and potential accessibility measures, with each type offering different insights depending on the context (Talen, 2003; Zhang & Han, 2021). Distance measures and cumulative opportunities focus on quantifying accessible opportunities within specific distances, times, or costs, a method widely utilized across various studies employing buffer areas and network analysis (Hansen, 1959; Handy & Niemeier, 1997; Silva et al., 2018; Rigolon, 2017; Quatrini et al., 2019). The potential accessibility measure, grounded in the gravity concept, assesses accessibility by considering the distance decay effect on opportunity availability across different zones (Nicholls, 2001). The Two-Step Floating Catchment Area (2SFCA) method, introduced by Radke and Mu (2000) and later refined by Luo and Wang (2003), incorporates population demand into the accessibility equation, addressing limitations of previous models by accounting for both distance decay and supply-demand interactions (Wu, Ye et al., 2017; Dai, 2011; Chen & Yeh, 2018). Despite its advancements, it assumes equal access within its catchment area, overlooking travel costs and service competitiveness. Subsequent enhancements, such as the Enhanced 2SFCA (E2SFCA) (Luo & Wei, 2009), Dynamic 2SFCA (McGrail & Humphreys, 2014), Nearest Neighbor 2SFCA (Jamtsho et al., 2015), and Three-Step Floating Catchment Area (3SFCA) method (Wan, Zou & Sternberg, 2012), have further refined the model's precision and utility.

In urban accessibility analyses, distance is primarily measured using two methods: straight-line distance (SLD) and network distance (ND), each may yield differing accessible area estimates (Mears & Brindley, 2019). Research indicates that reliance on SLD may misrepresent the actual interaction between population distribution and environmental features. In contrast, ND’s superior ability reflects a refined genuine spatial characteristic of spatial features (Quatrini et al., 2019). For instance, accessibility simulations using SLD can be skewed by the proximity of parks to residential areas without considering the real spatial structure of road networks and physical barriers such as fences, which significantly influence accessibility (Comber, Brunsdon & Green, 2008; Cracu et al., 2024). Consequently, employing ND can effectively reduce the overestimations typically associated with SMA assessments (Li, Du et al., 2019; Mears & Brindley, 2019).

While location-based measures are extensively employed in assessing urban accessibility, they often fail to adequately consider the individual dimension. Traditionally, individual perspectives are represented by socia-demographic variables like age, income, and gender, employing a segmentation approach (Titheridge et al., 2010). However, recent studies have highlighted how socio-demographic preferences significantly influence accessibility assessments, for instance, gender disparities in park access (Ode Sang et al., 2016) and older individuals perceiving lower accessibility compared to their younger counterparts (Yang et al., 2022). Furthermore, investigations have suggested that the spatial distribution of parks does not always serve all community segments equitably (Guo et al., 2020; Gong, Ng & Zheng, 2016). Relying only on objective measures such as travel time or distance PPA experiences of individuals or specific groups, potentially limits the connection between accessibility and social inclusion, as measured accessibility may not fully reflect reality (Lättman et al., 2016a; Curl, Nelson, & Anable, 2011; Pot et al. 2021). By incorporating the characteristics and preferences of diverse social demographics into the planning and design of Urban Green Spaces (UGS), urban planners can promote social justice and equity (Anguelovski, 2016; Rutt & Gulstrud, 2016).

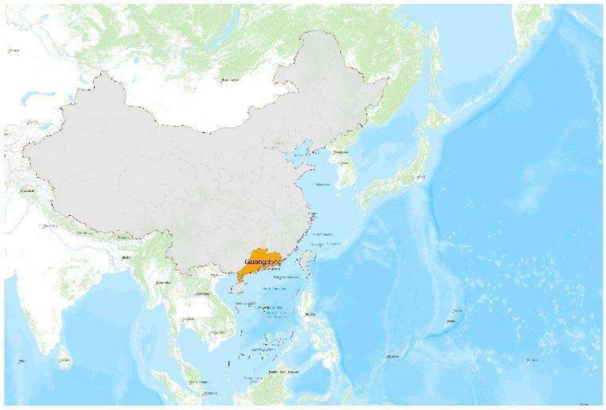
To understand subjective aspects of accessibility such as perceptions, knowledge, preferences, and abilities, PPA could be assessed through self-reported scales on the ease of reaching destination (Lättman et al., 2016a). PPA represents a human-centered evaluation influenced by subjective factors such as personal experience and preferences, in addition to objective factors like distance and park service areas. Research has highlighted the disparities between SMA and PPA, such as the presence of gaps between SMA and PPA to workplaces and jobs and train station (Budd and Mumford, 2006; Ryan et al., 2016). Ryan and Pereira (2021) found that SMA tends to overestimate accessibility levels and underestimate accessibility inequalities to healthcare centres and supermarkets among the elderly. To date, a small number of studies have explored the relationship between SMA and PPA, aiming to understand how these measures complement and relate to one another (Budd and Mumford, 2006; Curl et al., 2015; Laatikainen et al., 2015; Lättman et al., 2018; Ryan and Pereira, 2021; Ryan et al., 2016; El Murr, Boisjoly & Waygood, 2023).

Method selection in SMA for UGS planning plays a critical role, as the choice of distance measure (SLD vs. ND), travel time calculation (mean vs. population-weighted measurements), and modelling methods (buffer vs. 2SFCA) significantly influences UGS accessibility outcomes (Ma, Brindley, & Lange, 2022). According to the authors' knowledge, no study has directly compared results of eight distinct SMA methods (research question 1 within this work) nor assessed their relationship with PPA (research question 2). Identifying the SMA model that most accurately reflects PPA to UGS is critical, which may enhance the accuracy and equity of UGS accessibility assessments.

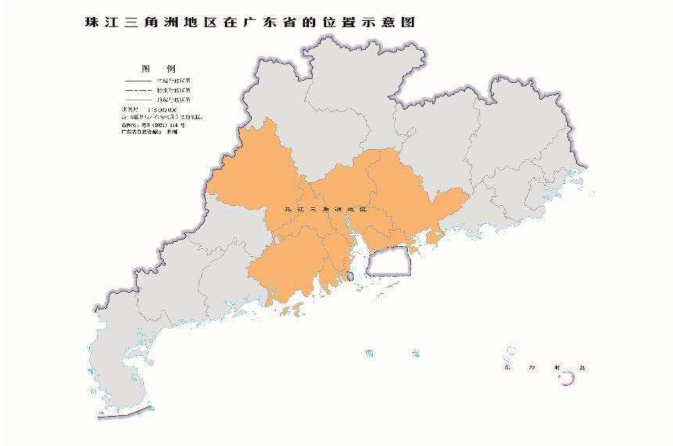
3 Data and Methods

3.1 Site Selection: Guangzhou, China

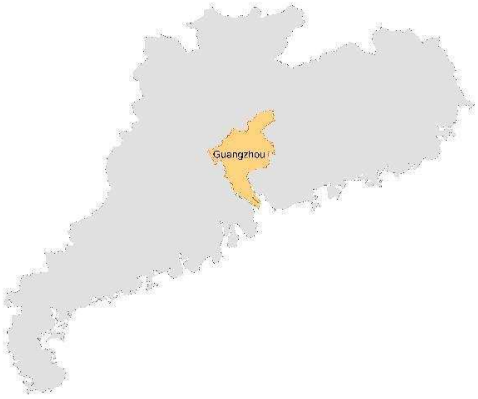
According to the 2020 China Census and subsequent analyses, Guangzhou ranks among China’s seven mega-cities, positioned as the foremost urban centre in southern China and the capital of Guangdong Province (Figure 1 (a) and (b)). Located at the heart of Guangdong and a key component of the Pearl River Delta (Figure 1 (c)), Guangzhou is located in one of the world’s densest metropolitan areas. The city comprises of eleven districts (Figure 1 (d)), with six central ones forming the main urban area, overseeing a total of 142 street communities (Guangzhou Statistical Yearbook, 2021).



(**a**) Location of Guangdong province in China



(**b**) Location of Guangdong province in Pearl River Delta
Source: Pearl River Delta regions in Guangdong Province
Available Online: http://nr.gd.gov.cn/map/bzdt/Index.aspx



(**c**) Location of Guangzhou in Guangdong

(**d**) Spatial administrative areas of Guangzhou

Figure 1. Location of study area, Guangzhou and administrative district division. (a) Location of Guangdong province in China; (b) location of Guangzhou in Pearl River Delta region; (c) location of Guangzhou in Guangdong; (d) spatial administrative areas of Guangzhou.

During 2010 to 2020, Guangzhou experienced significant population growth of approximately 27%, prompting the local government to re-evaluate its urban parks strategy with a sustainable development approach (Guangzhou Statistical Yearbook, 2021). Despite aims set in the “Guangzhou UGS System Planning (2010-2020)” to increase per capita public parks to 18 square meters, there remains a shortfall in achieving this target. The city’s forestry and landscape authorities have set ambitious goals for park construction up to 2035, including extending the 500-meter service radius of parks to cover 85% of the area, highlighting the prioritisation of park accessibility and the need for parks to align with residents’ usage patterns and behavioural tendencies.

As previously mentioned, owing to limitations in the data availability and for simplicity, urban parks, a critical subset of UGS, were delineated and chosen as the primary subjects of analysis for this study.

3.2 Measurement Methods

As highlighted in the literature review, there is no single approach to measure urban greenspace and as measuring techniques develop, an increasing number of studies stressed the importance of the combination of algorithmic models and spatial processing techniques for a comprehensive assessment of the accessibility of parks. There is also an increasing focus on both spatial and perceived dimensions of park accessibility assessment.

3.2.1 Eight SMA Approaches

Although the type of measurements depends on the specific studying purpose of the study, all the measurements consist of three elements: (1) people as the demand, (2) UGS as the supply, and (3) road / walking networks as the physical connection. Corresponding to the primary factors of park accessibility in this research, the three components are residents, parks, and paths, which were not fragmented but mutually restricted and related to each other. This highlights the need for coordination between the three elements to maximise park accessibility.

As highlighted in the literature review, the characteristics of residential populations (such as age and income levels) have an impact on park accessibility; and in return, parks affect people's proximity not only in the spatial dimension but also from service provision aspects (e.g., capacity, quality, popularity etc.) (Zhang et al., 2017; van Dillen et al., 2012).

Therefore, considering the three core subjects of accessibility discussed above, this study presented empirical, simulation and comparative analyses of park accessibility assessment methods and results in terms of model types, distance measurement methods and individual socioeconomic differences. These accessibility measurement methods include the buffer analysis of container methods, the network analysis method, and the 2SFCA method, and additionally, their derivative approaches developed from the regular model. These derived method models have been briefly described in Table 1, and can be explored in detail in previous work by the authors (Ma, Brindley & Eckart, 2022).

Table 1. Eight types of SMA by different distance measures and models

Distance measurement	**Model**			
	General Buffer (GB)	Preference-weighted Buffer (PWB)	Mean Two-Step Floating Catchment Area (M2FCA)	Preference-weighted Two-Step Floating Catchment Area (PW2SFCA)
Straight-linear distance (SLD)	(a) GB-SLD	(b) PWB-SLD	(c) M2SFCA-SLD	(d) PW2SFCA-SLD

	Straight-linear distance buffers; none-weighted walking time	Straight-linear distance buffers; none-weighted walking time	Straight-linear distance 2SFCA; none-weighted walking time	Straight-linear distance 2SFCA; preference-weighted walking time
Network distance (ND)	(e) GB-ND	(f) PWB-ND	(g) M2SFCA-ND	(h) PW2SFCA-ND
	Network distance buffer; none-weighted walking time	Network distance buffer; preference-weighted walking time	Network distance 2SFCA; none-preference weighted walking time	Network distance 2SFCA; preference-weighted walking time

Buffer and network analyses are instrumental in assessing park accessibility, with buffer analysis lauded for its simplicity and service radius focus, and network analysis for its path optimisation via road distance, providing a more accurate representation of park accessibility (Mear & Brindley, 2019). These methods proceed through four steps: identifying park entrances, determining population centres, setting service radii based on travel costs, and calculating the number of individuals served, thus evaluating a facility's spatial service capacity and accessibility level. The Two-Step Floating Catchment Area (2SFCA) method further refines this by establishing catchments for each supply object based on travel costs, then calculating capacity-to-population ratios for parks (using equations 3-1 and 3-2 below), illustrating their ability to meet population needs within their service radius. This process involves setting parks and residential points as search centres to evaluate park accessibility per capita after special weighting, addressing spatial interactions often overlooked in conventional accessibility assessments using buffers and network analysis.

1st step: For each park (j), $ATP_j = S_j / \sum_{k\in\{d_{jk}\}} \quad R_k$ (Equation 3-1)

2nd step: For each population area (i), $A_i \ = \sum_{j\in\{d_{ij}\}} \quad ATP_j$ (Equation 3-2)

The first step of a 2SFCA is generating a service catchment (S_j) with the travelling distance (d_{jk}) for each park (j) and adding up the population (R_k) within this area to calculate an area-to-population ratio (ATP_j). The second step is accumulating the ATP_j, where the population consists of people located in the catchment (R_i) that covers a travelling distance (d_{ij}) from each population location (i). For full details see Table S1 in the supplementary materials.

Table S1. 2SFCA model variables counterpart of the practical data for SMA measurements of parks

Elements in the 2SFCA model	Descriptions	Data in practice	Type of variables
d	Service radius of parks	Proper walking distance	Textual attributes; Input

S	Parks' service area within its service radius for pedestrians	First catchment areas	Spatial location with attributes; Output and Input
j	Accesses to parks	All accesses of parks	Spatial location; Input
R	Population counts	Grid population data	Spatial location with attributes; Input
i	Population locations	Centroids of each population grid	Spatial data; Input
ATP	Service capacity (size) of each park by its serving people	Area-to-population ratio	Textual attributes; Output and Input
A	Final accessibility indicator of each residential region	Total area of parks that serves the residential region within walking thresholds	Spatial location with attributes; Output

As outlined above (Table 1), this study enhances the foundational SMAmeasurement method by incorporating demographic preference variations in walking time as spatial weight differences among the population compositions of various areas into the spatial model. Service radii adjustments reflect varied resident travel time preferences, with demographic characteristics influencing accessibility model weights based on walking distance acceptance. The principal weighting formula is presented as Equation 3-3. A detailed introduction to this method can be found in the research conducted by Ma, Brindley, and Eckart (2022).

$T_i = \sum_{n}^{j=1} \frac{D_j}{DG} \times MT_{D_j}$ (Equation 3-3)

Whereby T_i indicates the acceptable walking time for residential point *i*. D_j is the population count of the *j*st group of the correlated demographic group. *DG* is a total count of the correlated population group. *n* represents the number of groups of *DG*. MT_{D_j} is the statistical mean time for D_j. This accessibility indicator was then classified on a five-point scale from 'Very poor' (value of 1) to 'Very good' (value of 5) using the Natural Breaks (Jenks) classification method.

GB and M2SFCA accessibility metrics were based on per capita park area occupancy within a 19.4-minute walking distance and informed by field-survey-derived walking time preferences. This measurement is in line with distances used in other similar researches (Steuteville, 2008; Ayala et al., 2022; Capasso Da Silva, King & Lemar, 2020).

3.2.2 PPA Measurement Method

Spatial perception, as described by Wang et al. (2023) and within Nasar's (1989) framework, involves the transformation of physical environments into subjective experiences, influencing emotions, well-being, and behaviours in urban spaces. This process, wherein urban emotions impact happiness and subsequently spatial behaviour, highlights a measurable influence of the physical environment on individuals. Furthermore, Ewing and Handy (2009) identify the interplay between physical characteristics and walking behaviour, noting how perceptions of urban design affect walkability. Accessibility measurements encompass both physical proximity and public perceptions.

This study integrates these concepts, as depicted in Figure 2, viewing park choice as a result of both spatial distance and park attractiveness, with the public's experiential evaluations reflecting their perceived park attributes, thereby contributing to our understanding of PPA to parks.

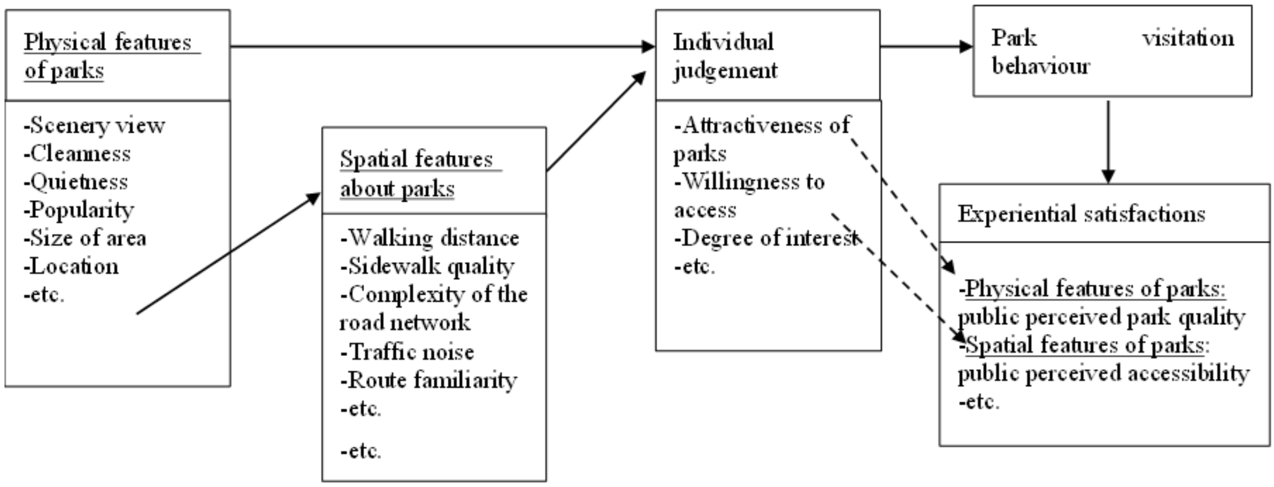


Figure 2. Conceptual framework of the formation of the public perception on park visitation (Adapted from Ewing et al. (2009, p. 67)).

This study investigated public perception of park accessibility through experiential satisfaction. This approach allows for the reflection of both physical and spatial characteristics of parks within perception dimensions. Emphasising public perception of accessibility, the study employs a 'Satisfaction with the Overall Walking Experience' (SoWEA) indicator, gathered via questionnaire using a Likert scale. This method quantifies the impact of park spatial features on accessibility, drawing on practices from prior research on PPA in various contexts (e.g., Lättman, Olsson and Friman, 2018; Scheepers, 2016; Wang et al., 2015), showcasing its applicability in evaluating PPA to parks and other amenities.

3.3 Data

3.3.1 Data Collection

The data utilised in this study included both primary data collected through field surveys and a range of existing secondary data.

The field survey data (used for PPA assessment in this study) were gathered via questionnaires, which was administered to capture the use status of urban parks by residents in the case study area, including the residential perceived and preferred dimensions of the characteristics of parks, including PPA and preferred walking time, and sociodemographic information, e.g., age, gender, and education level.

The data collection for this study occurred from November 2019 to January 2020. A small portion (130 out of 2,360) of early-stage pilot data was gathered via paper-based questionnaires through face-to-face interviews. Due to COVID-19 restrictions, the methodology shifted exclusively to online questionnaires. Existing research suggests that online surveys typically exhibit higher social desirability and comparably lower bias than paper surveys (Chang & Krosnick, 2009; Kreuter, Presser & Tourangeau, 2008; Dodou & de Qinter, 2014), implying the methodological shift in this study likely had minimal impact on the data's integrity.

The raw data used in assessing the SMA of parks consists of four types of secondary data: 1) urban parks from OpenStreetMap (OSM) (https://www.openstreetmap.org/); 2) The latest census data (by age, education, gender) within the administrative streets from the Statistic Bureau of Guangzhou Municipality (open access via: http://tjj.gz.gov.cn/stats_newtjyw/tjsj/pcsj/d6crkpc/index.html); 3) Population counts at 250-meter grid cells from the Global Human Settlement Layer (https://ghsl.jrc.ec.europa.eu/); 4) Road networks dataset from OSM.

3.3.2 Data Analysis Tools

Geo-spatial information plays a crucial role in evaluating the accessibility of urban parks, necessitating spatial analysis to aid in park planning and renewal. This research employs GIS for data storage—including urban parks, population, and network data—data preprocessing, spatial analysis, and the visualisation of results.

This research used spatial calculations within ArcGIS 10.7.1 for conducting the analysis and the comparison between the SMA of parks and the PPA of parks in the same street, taking the street level as the population collective unit. Quantitative analysis was the primary method for survey data analysis, including Chi-square tests and cross-tabulation, undertaken using SPSS Statistics 26.

4 Results and Discussions

There are three primary outputs demonstrating differences between types of accessibility in Guangzhou: 1) In response to Research Question 1 (comparing different SMA outputs), Section 4.1 explored distributions of accessibilities calculated by the eight approaches were illustrated by pie charts (Figure 3; for full details see Table S2 in the supplementary material) and in in each district (see Figure 4); 2) In relation to Research Question 2 (exploring differences in the spatial distribution of SMA approaches), Section 4.2 investigated spatial distribution (Figure 5) and spatial clustering features (Figure 6) of eight types of SMA; 3) In response to Research Question 3 (comparing SMA and PPA outputs), Section 4.3 reviewed the extent of divergence between SMA and PPA attributable to different spatial modelling approaches.

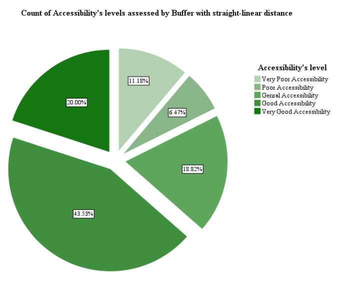
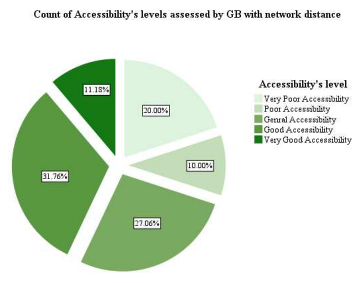
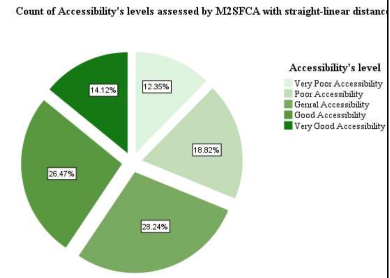
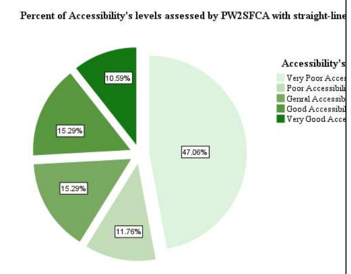
4.1 Differences Between the Eight Types of SMA

GB-SLD revealed over 60% of Guangzhou's streets provide good foot access to parks (Figure 3 (a)). By comparison, the M2SFCA-SLD approach, utilising the 2SFCA, showed only 40% of areas had good park accessibility (Figure 3 (c)), indicating GB-SLD identified around 20% more high accessibility regions. M2SFCA-ND analysis showed accessibility levels closely aligned with those by GB-ND (see Figure 3 (e) and (g)), more so than the M2SFCA-SLD's resemblance to GB-SLD. This supports the previous finding that the overestimation of SMA can be reduced through ND's use (Li, Du et al., 2019; Mears & Brindley, 2019).

The PWB-SLD accessibility model showed over 70% enjoying satisfactory access and 15.3% achieving very high levels (Figure 3 (b)). While PW2SFCA-SLD analysis indicated more areas of low than high accessibility, with nearly half of Guangzhou regions having 'Very Poor Accessibility' to parks and only about 10% of streets offering easy access (Figure 3 (d)). Similar to this, the PWB-ND and PW2SFCA-ND models showed higher proportions in poor park accessibility (Figure 3 (f) and (h)). It suggested that the PW method could usually detect lower park accessibility compared to models using non-weighted walking distance (except for PWB-SLD). This emphasises that the variance between populations affecting accessibility results significantly should be considered as local differences that are more comprehensive and multi-level indicator systems and broader in its scope of assessment (Porta & Renne, 2005) to be incorporated into spatial models of accessibility assessment. In addition, previous findings stated that the spatial distribution of parks might not serve certain groups equitably (Guo et al., 2020; Gong, Ng & Zheng, 2016), highlighting the necessity of park planning and assessment that are tailored to the use characteristics and preferences of different social demographics (Anguelovski, 2016; Rutt & Gulstrud, 2016).

Distance measurement	**Model**							
	General Buffer (GB)		**Preference-weighted Buffer (PWB)**		**Mean Two-Step Floating Catchment Area (M2FCA)**		**Preference-weighted Two-Step Floating Catchment Area (PW2SFCA)**	
Straight-linear distance (SLD)	(a) GB-SLD		(b) PWB-SLD		(c) M2SFCA-SLD		(d) PW2SFCA-SLD	
	Accessibility Level	Percent (%)	Accessibility Level	Percent (%)	Accessibility Level	Percent (%)	Accessibility Level	Percent (%)
	Very Poor	11.18	Very Poor	17.06	Very Poor	12.35	Very Poor	47.06
	Poor	6.47	Poor	10.59	Poor	18.82	Poor	11.76
	General	18.82	General	28.82	General	28.24	General	15.29
	Good	43.53	Good	28.24	Good	26.47	Good	15.29
	Very Good	20.00	Very Good	15.29	Very Good	14.12	Very Good	10.59
Network distance (ND)	(e) GB-ND		(f) PWB-ND		(g) M2SFCA-ND		(h) PW2SFCA-ND	
	Accessibility Level	Percent (%)	Accessibility Level	Percent (%)	Accessibility Level	Percent (%)	Accessibility Level	Percent (%)
	Very Poor	20.00	Very Poor	32.94	Very Poor	22.94	Very Poor	34.71
	Poor	10.00	Poor	9.41	Poor	14.71	Poor	18.24
	General	27.06	General	27.06	General	20.59	General	20.59
	Good	31.76	Good	18.82	Good	22.94	Good	15.88
	Very Good	11.18	Very Good	11.76	Very Good	18.82	Very Good	10.59

Table S2. Distributions of the SMA levels by eight types of models (a-h)

<table>
<tr><td>Distance measurement</td><td colspan="4">Model</td></tr>
<tr><td></td><td>General Buffer (GB)</td><td>Preference-weighted Buffer (PWB)</td><td>Mean Two-Step Floating Catchment Area (M2FCA)</td><td>Preference-weighted Two-Step Floating Catchment Area (PW2SFCA)</td></tr>
<tr><td>Straight-linear distance (SLD)</td><td>
</td><td>
</td><td>
</td><td>
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<tr><td></td><td>(a) GB-SLD</td><td>(b) PWB-SLD</td><td>(c) M2SFCA-SLD</td><td>(d) PW2SFCA-SLD</td></tr>
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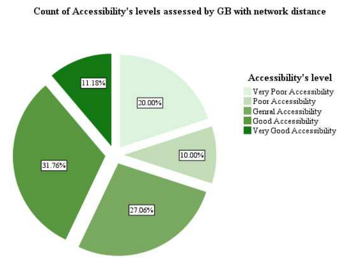
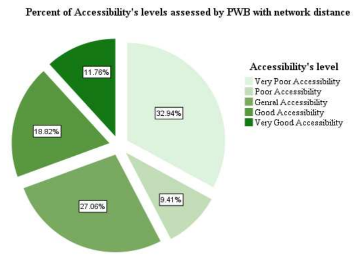
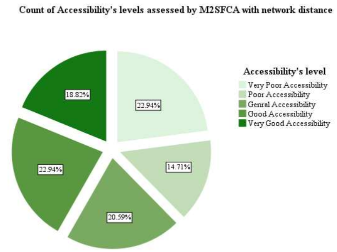
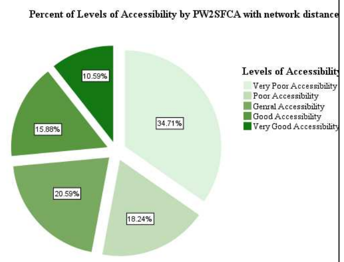
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>(e) GB-ND</td>
<td>(f) PWB-ND</td>
<td>(g) M2SFCA-ND</td>
<td>(h) PW2SFCA-ND</td>
</tr>
</table>

Figure 3. Distributions of the SMA levels by eight types of models (a-h)

Pertaining to the SMA across diverse districts, distinct spatial modelling methods exhibit variable performances. GB-SLD revealed that Panyu District accounted for the highest proportion of streets with ‘Very Good Accessibility’ (50%), indicating a high proportion of streets with very good access to parks (supported by the district being the suburb with the highest accessibility across all SMA approaches - Table 2). In contrast, previous research reported by Yang, Yang and Zhou (2022) identified large UGS inequalities in Panyu highlighting potential disparities with our findings. Yuexiu district has the highest accessibility levels (mean 4.22) (Table 2), featuring no poor accessibility streets by GB-SLD. In contrast, M2SFCA-SLD highlights Yuexiu lacking ‘Very Good’ access (Figure 4 (c)) especially. The primary distinction between GB and M2SFCA models lies in accounting for potential supply crowdedness, highlighting a significant measurement difference in areas with smaller parks or dense populations for high-density cities (Zhang & Han, 2021).

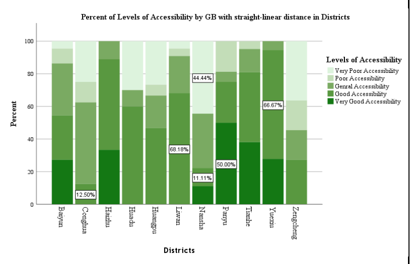
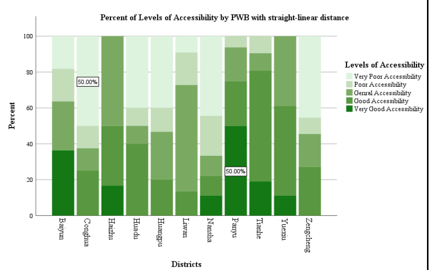
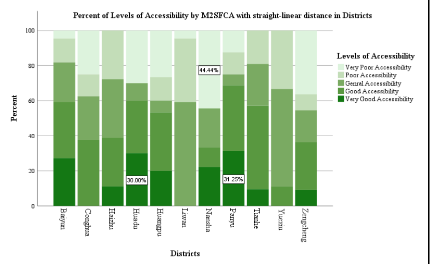
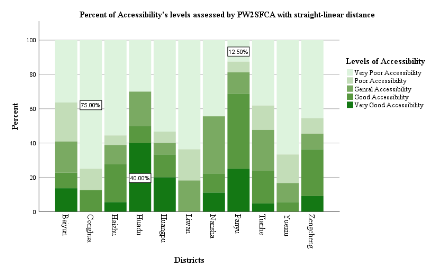
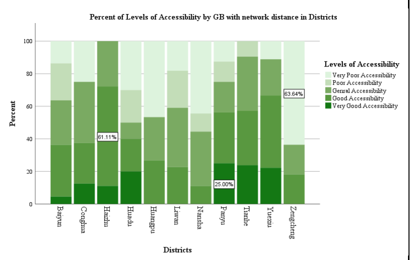
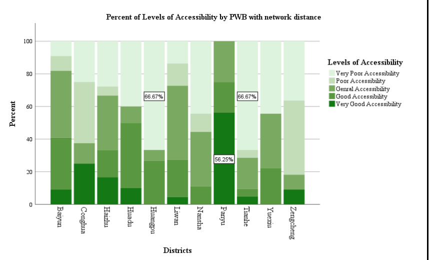
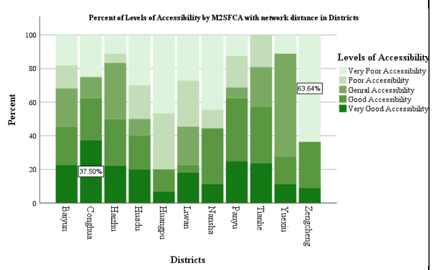
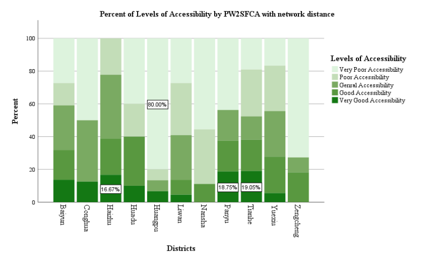
Distance measure ment	**Model**			
	General Buffer (GB)	**Preference-weighted Buffer (PWB)**	**Mean Two-Step Floating Catchment Area (M2FCA)**	**Preference-weighted Two-Step Floating Catchment Area (PW2SFCA)**
Straight-linear distance (SLD)				
	(a) GB-SLD	(b) PWB-SLD	(c) M2SFCA-SLD	(d) PW2SFCA-SLD
Network distance (ND)				
	(e) GB-ND	(f) PWB-ND	(g) M2SFCA-ND	(h) PW2SFCA-ND

Figure 4. Percents of the SMA levels in districts by eight types of models (a-h)

Table 2. mean values of accessibility in districts by eight modelling approaches

Districts	Modelling Approach (a) GB-SLD		(c)M2SFCA-SLD		(e)GB-ND		(g)M2SFCA-ND		(b)PWB-SLD		(d)PW2SFCA-SLD		(f)PWB-ND		(h)PW2SFCA-ND	
	Mean	St.d	Mean	St.d	Mean	St.d	Mean	St.d	Mean	St.d	Mean	St.d	Mean	St.d	Mean	St.d
Urban Areas																
Baiyun	3.64	1.14	3.64	1.18	2.91	1.15	3.18	1.44	3.18	1.56	2.41	1.44	3.23	1.07	2.77	1.41
Haizhu	4.22	0.65	3.22	1.00	3.83	0.62	3.44	1.25	3.67	0.77	2.17	1.47	2.89	1.45	3.33	1.03
Yuexiu	4.22	0.55	2.78	0.65	3.67	1.19	3.17	1.04	3.72	0.67	1.56	0.92	2.33	1.28	2.72	1.18
Huangpu	2.87	1.30	3.07	1.58	2.33	1.35	2.00	1.31	2.27	1.22	2.4	1.72	1.93	1.39	1.47	1.13
Liwan	3.55	0.80	2.55	0.60	2.64	1.05	2.59	1.44	2.77	0.81	1.55	0.80	2.91	1.06	2.32	1.13
Tianhe	4.14	0.85	3.48	0.93	3.71	0.96	3.62	1.07	3.90	0.83	2.38	1.32	1.76	1.22	2.90	1.45
Suburb Areas																
Huadu	3.00	1.41	3.30	1.70	2.80	1.62	2.80	1.62	2.50	1.43	3.30	1.77	2.80	1.62	2.50	1.58
Nansha	2.44	1.51	2.67	1.73	2.11	1.17	2.56	1.67	2.22	1.48	2.44	1.51	2.11	1.17	1.67	1.00
Panyu	4.06	1.18	3.63	1.41	3.44	1.36	3.44	1.41	4.19	0.98	3.63	1.31	4.31	0.87	2.69	1.66
Conghua	2.50	1.07	2.75	1.28	3.00	1.41	3.50	1.69	2.13	1.36	1.50	1.07	2.63	1.60	2.25	1.49
Zengcheng	2.36	1.29	2.64	1.50	1.91	1.30	2.18	1.66	2.27	1.35	2.45	1.57	2.00	1.18	1.73	1.27
Overall	3.55	1.21	3.11	1.23	3.04	1.29	3.00	1.43	3.14	1.29	2.31	1.45	2.67	1.40	2.49	1.38

Red cell indicates the highest one among districts for the approach; Blue cell indicates the lowest one among districts for the approach.

Comparing GB-ND and GB-SLD analysis, results (Figure 4 (e)), show comparable levels of accessibility for Zengcheng, Haizhu and Panyu districts in relative terms. However, absolute values tended to be overestimated for SLD compared to ND approaches. Additionally, Table 2 revealed that Zengcheng District had the lowest mean accessibility value (1.91), lower than its GB-SLD counterpart (2.36). This diminished accessibility attributed to the ND measure (in comparison to SLD) could be due to the presence of smaller city clusters with inadequate urban infrastructure within the Zengcheng district (Zhou, He, Wu & Zhang, 2022), which constrains the connectivity between parks and residents throughout the spatial simulation.

Analysis of M2SFCA-ND revealed distinct district variations, with Huangpu, not Zengcheng (analysed by GB-SLD and GB-ND), having the lowest mean accessibility (2.00) (Table 2) with under 20% of areas having ‘Good’ or ‘Very Good’ access, uniquely the lowest among districts (Figure 4 (g)). The emergence of the area with reduced accessibility, resulting from the foundational shift from the GB model to 2SFCA, typically indicates a deficiency in the region’s attention to the balance between supply and demand for parks (Chen & Yeh, 2019). Specifically, it suggests a lack of consideration for the resource congestion caused by high population density, which in turn leads to an implicit shortfall in accessibility.

PWB-SLD revealed Panyu District has superior park access (over 50% streets with excellent accessibility as shown in Figure 4 (b), with mean 4.19), while Conghua exhibited the lowest levels with a mean of 2.13 (Table 2). The variability in district accessibility levels assessed by PWB-SLD was higher compared to PWB-ND, yet consistent with other models with SLD measures. Notably, despite utilising the PW variable, these findings are similar to those from the M2SFCA-ND analysis. It suggests that using ND measure for M2SFCA or PWB could equally reduce the variability caused by SLD and implies that the implementation of the 2SFCA method signifies an advancement in incorporating population demand within accessibility assessments (Wu et al., 2017; Dai, 2011), and to a certain extent, achieves the objective of integrating weighted preferences for population travel distances.

PW2SFCA-SLD found 75% of Conghua District's streets in the 'Very Poor Accessibility' category (Figure 4 (f)) ranking lowest (mean 1.50) (Table 2), contrasted with just 12.5% in Panyu, leading to a mean value of 3.63. Although this is consistent with PWB-SLD results, Haizhu and Yuexiu witnessed significant increases in 'Very Poor Accessibility' (15% and 14% respectively) using PW2SFCA-SLD analysis. This reflects the limitations of the SLD measure for accessibility modelling. It was explained by previous research findings that even if parks are in close linear proximity to residential areas, the real spatial structure of road networks and the barriers created by fences/other barriers around parks and residences can impact the outcomes of accessibility spatial simulations established using the SLD measure (Comber, Brunsdon & Green, 2008; Cracu et al., 2024). This study further underscores the inherent instability of the SLD measure, which is not easily overcome despite the adoption of various methodological combinations, whether PW or not, and regardless of the model types (GB/2SFCA) employed.

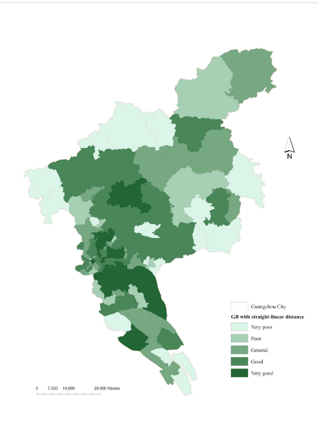
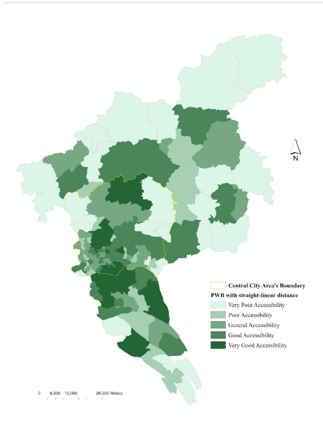
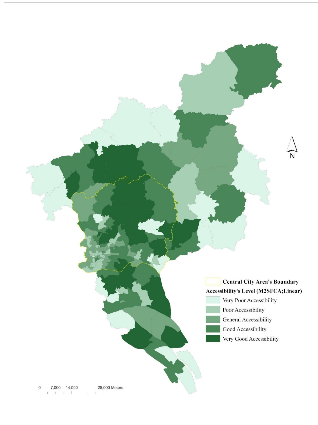
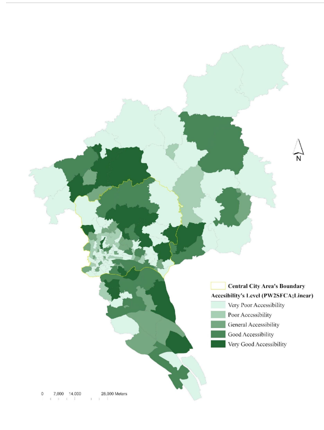
Tianhe District exhibited the lowest park accessibility (mean 1.76) by PWB-ND, a significant decline from other approaches (see Table 2). This stark contrast highlighted the influence of regional population composition on park accessibility outcomes. Conversely, Panyu District maintained high accessibility (mean 4.31), lacking poor accessibility, and with 56.25% of areas rated as 'Very Good Accessibility' (Figure 4 (f)). The comparison across different distance measures (SLD/ND) and weighting approaches underscored Panyu's consistently favourable park access. This diverges from the findings of some previous studies. Yang, Yang and Zhou (2022), employing a geographically weighted regression model, identified inequities in the distribution of parks in the Panyu district; Xu et al. (2023) highlighted the high population density in Panyu district, marking it as a primary area in need of parks development in Guangzhou. This suggests that accessibility analyses may not accurately reflect the degree of supply-demand matching, especially since these SMAs are calculated based on the GB model, overlooking indicators of supply-demand distribution considered in the 2SFCA model.

Huangpu had the lowest accessibility level (mean 1.47) by PW2SFCA-ND (Table 2), as previous ND approaches shown, highlighting the ND spatial metric enables to reveal poorest accessibility in centre city, suggesting an urgent need for road network improvements in inner city area, especially Huangpu and Tianhe, to enhance park accessibility. However, Tianhe had a higher prevalence of ‘Very Good Accessibility’ streets (Figure 4 (h)), marking the disparity in urban infrastructure and planning across the streets in this district (Yang, Yang & Zhou, 2022).

The observed discrepancies in SMA attributed to slight variances in spatial simulation techniques, highlight the limitations of using a single method for accessibility assessment. This is particularly relevant in many Chinese cities, where simple metrics like UGS per capita or the proportion of land dedicated to parks fall short of addressing urban requirements (Liu, Remme et al., 2020). Despite varying advantages across different methodologies, adopting the ND measure combined with either 2SFCA or PW walking distance variables is recommended for more robust SMA evaluations in future urban planning.

4.2 Spatial Distributing Features of Eight Types of SMA

Whilst the previous section explored differences in SMA approaches (including differences between districts), this section, in line with Research Question 2, explores spatial patterns at a sub-district level. The GB-SLD analysis revealed ‘Very Poor’ park accessibility predominantly at urban fringes (Figure 5 (a)) and ‘High-High’ clustering in the city centre indicating uniformly high accessibility (Figure 6 (a)). Clusters (most of ‘Low-High’ and ‘Low-Low’ ones) in suburban area highlighted both the rarity of high accessibility and the commonality of poor access zones. M2SFCA-SLD revealed spatial heterogeneity like GB-SLD’s pattern in the city centre (see Figure 5 (a) and (c)), identifying significantly more ‘High-High Cluster’ areas, predominantly covering Tianhe District, majority of Baiyun and Haizhu Districts, with fewer ‘Low-Low Cluster’ areas detected (Figure 6 (c)). Both approaches ignored the effect of road network structure, which connects infrastructure and residents in reality, consequently failed to examine the refined spatial inequity of parks supply in these regions that have been stressed by other studies (e.g., Zhu et al, 2019; Yang et al., 2022).

<table>
<tr><td>Distance measure ment</td><td colspan="4">Model</td></tr>
<tr><td></td><td>General Buffer (GB)</td><td>Preference-weighted Buffer (PWB)</td><td>Mean Two-Step Floating Catchment Area (M2FCA)</td><td>Preference-weighted Two-Step Floating Catchment Area (PW2SFCA)</td></tr>
<tr><td>Straight-linear distance (SLD)</td><td>
</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td></td><td>(a) GB-SLD</td><td>(b) PWB-SLD</td><td>(c) M2SFCA-SLD</td><td>(d) PW2SFCA-SLD</td></tr>
</table>

<table>
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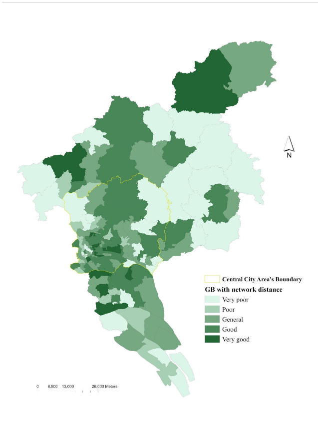
<td>
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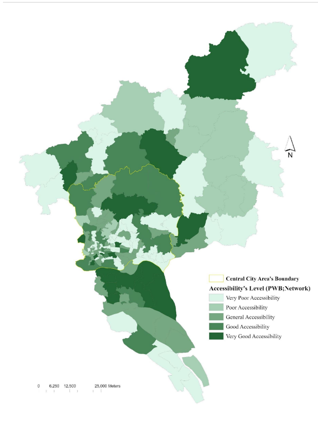
<td>
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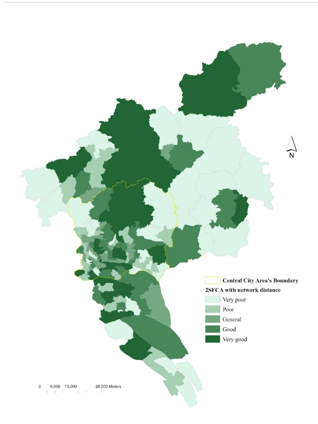
<td>
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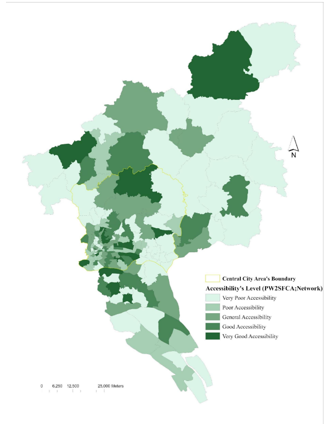
<td>
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<tr><td></td><td>(e) GB-ND</td><td>(f) PWB-ND</td><td>(g) M2SFCA-ND</td><td>(h) PW2SFCA-ND</td></tr>
</table>

Figure 5. A summary on spatial distributions of SMA levels evaluated by eight models (a-h)

Distance measurement	**Model**			
	General Buffer (GB)	**Preference-weighted Buffer (PWB)**	**Mean Two-Step Floating Catchment Area (M2FCA)**	**Preference-weighted Two-Step Floating Catchment Area (PW2SFCA)**

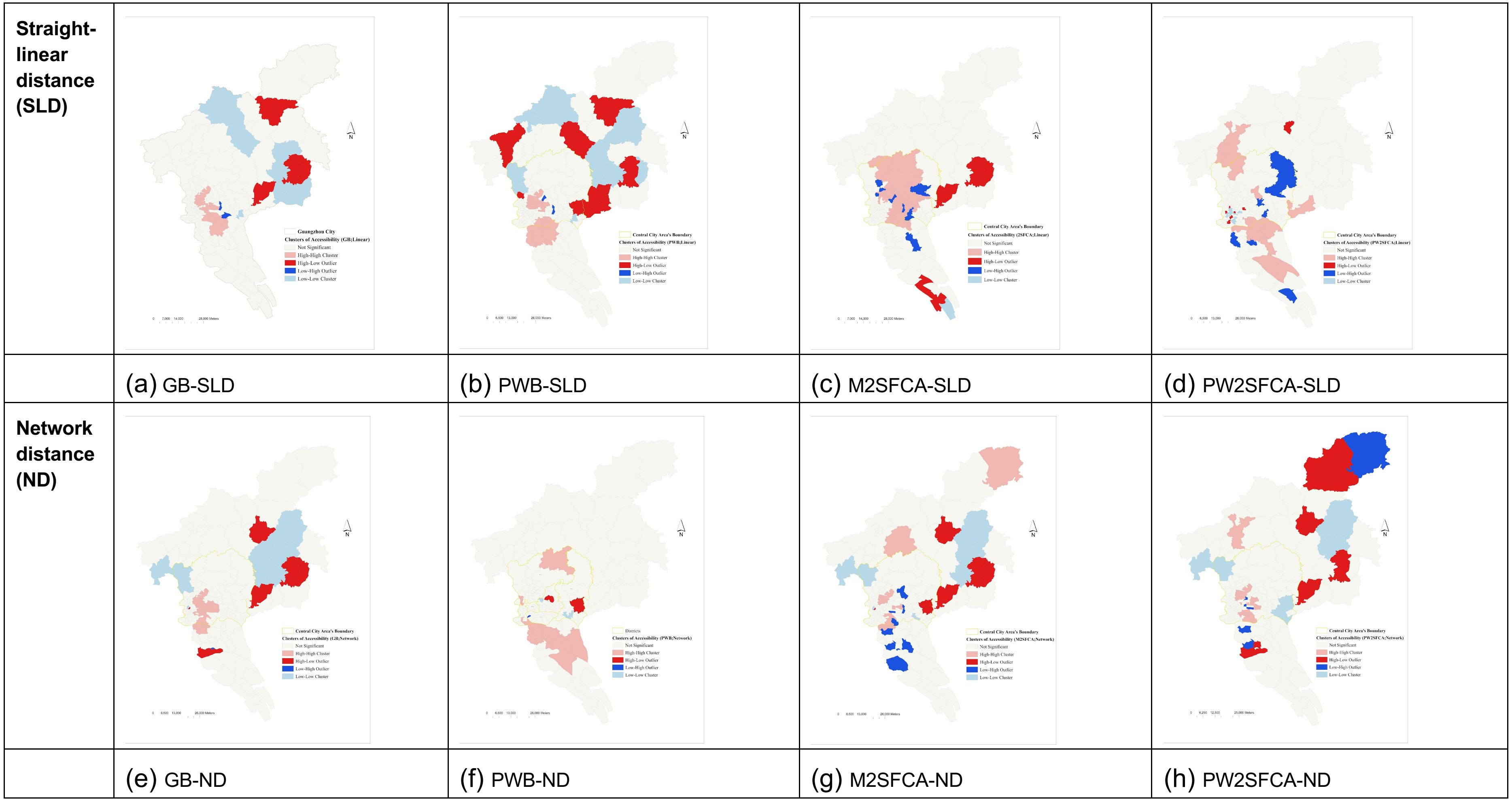

Figure 6. A summary on spatial clusters of eight types of SMA (a-h)

GB-ND (Figure 5 (e)) and M2SFCA-ND (Figure 5 (g)) park accessibility distribution highlighted poor park access mainly in Guangzhou's central-east, with scattered areas in the west, primarily outside the central urban zones. Additionally, along Guangzhou's north-south axis (where a complex road network structure is present) GB-ND demonstrated poor accessibility in both central and non-central urban areas, compared with GB-SLD. Referencing the aforementioned comparison between ND and SLD measures, in spatial models that do not account for population preference weighting and supply-demand matching (i.e., employing the 2SFCA approach), the inclusion of road network structures has universally resulted in a decline in accessibility outcomes reflecting the significance of local contexts in interpreting results (Mears & Brindley, 2019).

M2SFCA-ND detected clusters more frequently occurring outside the city centre, compared to M2SFCA with SLD measure. This discrepancy may stem from two factors: the potential for SLD overestimation in densely road-networked areas, leading to a concentration of perceived high accessibility in these central regions, and population density exacerbating SLD's overestimation. Mears and Brindley (2019) support this, noting that using straight-line distances may misrepresent the true relationship between population distribution and environmental features.

The consistent findings across four SMAs employing non-weighted walking distances underscore the achievements of planning and design in Guangzhou, that is, the planning and construction of the city's central axis which appears to have particularly facilitated the SMA of parks. This could be associated with a higher level of land use mix in the area, encompassing retail stores, various services, and amenities within a space, which can be regarded as a viable characteristic of land. Consequently, people may be encouraged to walk further for park visits in areas with a higher land use mix (Koohsari et al., 2019; Safaie et al., 2023).

PWB-SLD (Figure 5 (b)), compared to GB-SLD, indicated park accessibility with a similar spatial distribution yet expanded the scope of 'Very Poor Accessibility' areas, including more adjacent streets with limited park access (Figure 6 (b)). This phenomenon could be attributed to the homogeneous population composition across neighbouring streets, which likely share a similar reluctance for longer travel distances. Including population weighted variables (PW) in spatial modelling, accentuates the issue of insufficient park access in these regions, leading to an expanded spread of low accessibility areas upon integrating population preference weighting. Similar impacts of socio-demographic preference on accessibility assessment have been confirmed by previous studies. For example, Ode Sang et al. (2016) explained the gender differences affecting people's access to parks and Yang et al., (2022) revealed the elderly were more likely to perceive poorer accessibility than younger generations. After incorporating public preference across districts, contrast to GB-SLD's less varied accessibility across streets (Figure 6 (a)), 'Low-Low' areas of PWB-SLD park accessibility located in suburbs were often near 'High-Low' zones (Figure 6 (b)), exhibiting higher spatial variation.

PW2SFCA-SLD revealed low accessibility in the city centre compared to other methods (Figure 5 (d)) including 'Low-Low Cluster' spatial features, newly observed in central city areas (including Yuexiu, Liwan, and Haizhu districts) (Figure 6 (d)), designated streets with even 'General' accessibility as 'High-Low Outliers'. Conversely, more 'High-High Cluster' emerged in Huadu and Panyu, marking a first spatial pattern in the south, in comparison to previous methods.

As shown in Figure 5 (f), PWB-ND, differing from PWB-SLD and GB-ND, identified significant park accessibility deficits concentrated in the central city's Mideast and East, showcasing the pronounced influence of road networks and population preferences on accessibility evaluation. Furthermore, spatial clusters of SMA by PWB-ND revealed a 'High-High Cluster' in North Nansha (Figure 6 (f)). This contrasts with earlier approaches, indicating that Nansha's road networks and park placements, aligned with population preferences, likely contribute to improved accessibility. This may be attributed to the fact that the Nansha District is a newly developed area, where the concentration of small residential developments is relatively low, preserving a certain level of ecological resources. Consequently, this has precluded the occurrence of severe inequities in green space distribution (Yang et al., 2022).

PW2SFCA-ND analysis pinpointed areas along the western central axis enjoying relatively high access, and the central southwestern region within the main urban zone exhibiting enhanced accessibility (Figure 5 (h)). Analyses utilising the ND spatial metric (as shown in Figure 5 (c), (g), (d) & (h)) consistently highlighted increased accessibility along the central axis, reflecting the urban development strategy initiated in 1982. In addition, low accessibility zones in the central city, particularly in Huangpu's southeastern corner, contrast with 'High-High Clusters' in central areas including Haizhu, southern Baiyun, and southern Tianhe. These patterns also align closely with the central axis. This reflected ND's better capability in capturing realistic spatial features compared to SLD, revealing refined spatial pattern (Quatrini et al., 2019).

As expected and noted by previous authors, these differences explored above highlighted that different methods and contextual differences across locales can produce different results for measuring UGS accessibility and consequently require increased attention (Mears & Brindley, 2019).

4.3 Discrepancy between SMA and PPA

Research Question 3 of this work explores which SMA outputs best compare with perceived park accessibility (PPA). Existing research highlights a pronounced discrepancy between SMA and PPA, underscoring the necessity of integrating both spatial and perceptual dimensions to accurately evaluate the accessibility of urban parks (Cohen et al., 2010). Relying solely on one dimension compromises the authenticity and efficacy of accessibility assessments. Hence, enhancing the congruence between SMA and PPA is imperative. Consequently, this study not only contrasts the SMA of parks derived from various analytical methods but also examines their differences with PPA. By harmonising the SMA data of districts with PPA within identical measurement units (streets), a spatial analysis was conducted, culminating in the findings presented in Table 3, which quantifies the alignment between SMA and PPA through differential values.

Table 3 Comparison between eight types of SMA by different approaches and PPA

Modelling approaches of SMA	**Mismatch or Match**		
	Lower than PPA (%)	Equal to PPA (%)	Higher than PPA (%)
PW2SFCA-ND	41	20	39
PW2SFCA-SLD	58	22	20
PWB-ND	39	**25**	36
PWB-SLD	25	18	57
M2SFCA-ND	31	20	49
M2SFCA-SLD	33	19	48
GB-ND	30	**13**	57
GB-SLD	17	15	68

The table compares various SMA methodologies against PPA detailing their congruence or divergence. It categorises the alignment into three segments: ‘Equal to PPA’, signifying precise matches; ‘Lower than PPA’, denoting SMA underestimations of accessibility; and 'Higher than PPA’, indicating SMA overestimations relative to PPA perceptions. With the proportion of exact matches (‘Equal to PPA’) not exceeding 25%, the analysis underscores a general disparity between SMA outcomes and public perceptions, which can be caused by elements related to individual preferences that affect access to parks incorporated into the SMA method (Pot, van Wee & Tillema, 2021). Furthermore, among five analysed SMA configurations, there is a noticeable tendency for SMA to overestimate accessibility compared to PPA, as evidenced by a greater frequency of ‘Higher than PPA’ outcomes in over half of the instances (5 out of 8). This observation supports the findings of previous work that SMA tended to overestimate the PPA (e.g., Ryan & Pereira, 2021; El Murr, Boisjoly & Waygood, 2023).

The most notable discrepancy between SMA and PPA was observed with the application of the GB method, particularly when employing the ND measure, which exhibited the lowest concordance (‘Equal to PPA’) at a mere 13%. Furthermore, the GB-SLD method tended to overestimate accessibility, resulting in the most significant overestimation compared to actual public perceptions of park accessibility. This underscores previous discussions suggesting that the GB and SLD methods are likely to overlook actual spatial characteristics (Mears & Brindley, 2019; Apparicio et al., 2008), leading to reduced robustness in SMA modelling and a poorer match with PPA. In contrast, integrating PWB with ND markedly improved model alignment with PPA, as evidenced by the highest match rate (‘Equal to PPA’) of 25%. This approach also presented a more balanced distribution between underestimation and overestimation of PPA by SMA, with respective proportions of 39% and 36%. This indicates that enhancing SMA can be achieved not only by developing advanced models such as the enhanced 2SFCA or 3SFCA (e.g., Jamtsho et al., 2015; Wan, Zou & Sternberg, 2012) but also by incorporating the PW method and the ND measure to refine the basic buffer model, thereby improving SMA's alignment with PPA.

However, a solitary SMA metric falls short of genuinely evaluating the service status of parks. Factors such as variations in population demand, the distribution structure of spatial supply and demand (Ozguner, 2011), and their interdependencies necessitate a comprehensive consideration within the SMA modelling process (Peng & Xu, 2004; Dai et al., 2019). It should not be assumed that the PW method consistently ensures SMA aligns more closely with PPA. This is because when PW is integrated with the 2SFCA model, the models are inclined to underestimate PPA, irrespective of the inclusion of either ND or SLD measures, with 'Lower than PPA' proportions recorded at 41% and 58%, respectively.

Furthermore, this study highlights how incorporating demographic preferences into the modelling improves the correlation between spatial assessments and PPA (Table 4). Analysis of four models ('Group1' to 'Group4') through the variation in their 'Equal to PPA' proportions reinforced the benefits of integrating PW travel time across different methodologies and foundational models for closer SMA-PPA congruence. The PW distance factor consistently yielded non-negative differences among the model groups, indicating that weighting travel distance by population preferences generally bolsters SMA's accuracy in mirroring PPA, particularly when buffer analysis with ND is applied in spatial park accessibility modelling (Group 3), showing a 12% increase in regions where SMA aligns with PPA after applying PW adjustments. This could corroborate the necessity of incorporating population preference variables in SMA simulations (Pot, van Wee & Tillema, 2021; Tan et al., 2022) and their effectiveness in aligning with PPA.

Table 4. Impact of two factors (demographic preference weight of travel time and basic modelling method) on the extent of matching SMA assessment to PPA

Factor	Group	Model	Equal to PPA (%)	Difference (%)
Preference Weighted (PW) travel distance	Group1	(h) PW2SFCA-ND	20	0
		(g) M2SFCA-ND	20	
	Group2	(d) PW2SFCA-SLD	22	3
		(c) M2SFCA-SLD	19	
	Group3	(f) PWB-ND	25	12
		(e) GB-ND	13	
	Group4	(b) PWB-SLD	18	3
		(a) GB-SLD	15	
Basic modelling method	Group5	(h) PW2SFCA-ND	20	-5
		(g) M2SFCA-ND	25	
	Group6	(d) PW2SFCA-SLD	22	4
		(c) M2SFCA-SLD	18	
	Group7	(f) PWB-ND	20	7
		(e) GB-ND	13	
	Group8	(b) PWB-SLD	19	4
		(a) GB-SLD	15	

Regarding the 'Basic modelling method' factor, encompassing GB and 2SFCA types, results suggest that 2SFCA generally aligns more closely with PPA than the GB model, except in scenarios utilizing PW walking time and ND measure (Table S). In such cases, GB analysis (PWB-ND with 'Equal to PPA' of 25%) demonstrates a more precise fit to PPA compared to 2SFCA analysis (PW2SFCA-ND with 'Equal to PPA' of 20%). This deviation challenges the notion that 2SFCA, recognised for its nuanced consideration of supply and demand relationships in SMA (McGrail and Humphreys, 2009), consistently outperforms traditional models. It suggests that additional factors, such as travel time weighting and spatial metrics, may influence 2SFCA's accuracy in reflecting PPA, particularly regarding subjective perceptions of accessibility.

Building upon this, the study examined possibilities for enhancing the match between SMA and PPA by using varied travel distance (mean and PW). This was achieved by highlighting the discrepancies in the assessment of accessibility extents, whereby it delineated the variations in over- or under-estimations relative to PPA, as detailed in Table 5. The investigation revealed that spatial assessment models, which do not incorporate population preference attributes to modulate travel distances, exhibit a propensity towards overestimating accessibility. This trend was notably more pronounced ('Higher than PPA' versus 'Lower than PPA') when contrasted with the accessibility evaluations derived from PPA, which is inherently subjective and perception-driven. Such findings suggest that the overestimation of park accessibility by SMA with unweighted variables, in comparison to PPA, remains consistent regardless of the chosen spatial metric and the foundational assessment model. This is likely attributed to the challenge unweighted distance variables face in capturing subjective factors, given that PPA is an assessment centred around "people" and is influenced by subjective factors (such as experiences and preferences), not solely by objective factors (distance, park service area) (Tiznado-Aitken et al., 2020; Curl, Nelson & Anable, 2011; Ma & Cao, 2019).

Table 5. Impact of demographic preference weights of travel distance on the extent of SMA assessment diverging from the PPA

Factor	Group	Model	Lower than PPA (%)	Higher than PPA (%)	Deviating features
Travel distance	Preference Weighted (PW)	(h) PW2SFCA-ND	41	39	More underestimations
		(d) PW2SFCA-SLD	58	20	
		(f) PWB-ND	39	36	
		(b) PWB-SLD	25	57	More overestimations
	Unweighted	(g) M2SFCA-ND	31	49	More overestimations
		(c) M2SFCA-SLD	33	48	
		(e) GB-ND	30	57	
		(a) GB-SLD	17	68	

Remarkably, these overestimations were at least 15% more frequent than underestimations, with the disparity peaking at 51% for the GB-SLD case. Consequently, this elucidates a potential strategy to diminish the discrepancy—predominantly overestimation—between SMA and PPA, achieved by integrating the 2SFCA model with the SLD spatial metric into the SMA evaluative framework. It thereby offers a refined approach to gauge accessibility under scenarios where travel times are not weighted.

In contrast, the implementation of PW walking distance in four distinct assessment models resulted in a general trend where park accessibility, as determined by these models—with the notable exception of the PWB-SLD model—tended to underestimate PPA. This discrepancy between SMA and PPA was less pronounced within the ‘Preference Weighted’ category, exhibiting a range of 75%-82% in mismatch occurrences, as opposed to the 80%-87% range observed within the ‘Unweighted’ category. Such findings underscore the value of incorporating population preferences as critical indicators or variables within spatial modelling methodologies for accessibility assessment, thus achieving a closer alignment between objective measures and subjective perceptions of accessibility, as highlighted by Lättman, Olsson, and Friman (2016).

Notably, the integration of PW travel time alongside the ND spatial metric, particularly within the newly developed PWB-ND approach—which diverges from the traditional GB model in favour of the 2SFCA model, previously regarded as more advanced (Tao, Cheng & Liu, 2020)—has shown to significantly mitigate the mismatch between SMA and PPA outcomes, evidenced by an increased congruence in matched regions, up to 25%. Therefore, if the objective is to diminish the SMA’s tendency to overestimate accessibility relative to PPA, employing a combination of PW travel distances, the 2SFCA model, and the SLD spatial metric appears to be an effective strategy. This approach has led to a reduction in overestimated regions to 20%, thereby suggesting a promising avenue for refining the accuracy of SMA in reflecting PPA.

5 Conclusions

5.1 Limitations and Future Research

In this paper, we’ve embarked on a comparative study to examine park accessibility modelling utilising a variety of approaches. Despite achieving notable insights, our analysis faces several limitations that warrant attention for future research.

As with most data analysis our study suffers from a lack of the highest-precision data and an in-depth exploration of various accessibility analysis models, such as distance decay and the Three Step Floating Catchment Area (3SFCA). Future research should broaden the range of modelling techniques for park accessibility. Additionally, while our design did not support detailed field survey at the individual park level, with an average of only four samples per park from 2,360 respondents across 494 parks, our main focus was on the relationship between travel distance to parks and population characteristics, not on specific park preferences and their environs. Despite these challenges, we introduced an innovative methodology for assessing park accessibility, providing valuable insights into accessibility variations under different scenarios, informed by public perception.

5.2 Research findings

In this study, Research Question 1 compared the outputs of park accessibility using eight different SMA approaches. These findings reveal that the choice of modelling methods significantly influences these features, emphasising the necessity of selecting appropriate models that account for the local context’s unique impacts. The demonstration of eight SMA approaches has provided important evidence that weighting travel time by population preferences among correlated sociodemographic groups can mitigate the impacts of variations caused by both the model type and the distance measure on the park accessibility outputs. The discrepancies in outputs between the eight SMA models demonstrate small variations in spatial simulation techniques. This highlights the limitations of using a single method for measuring accessibility. Despite varying (dis)advantages across the eight models, this work highlights the importance of adopting the ND measure combined with either 2SFCA or PW walking distance variables for more robust SMA evaluations. This has important implications for future UGS accessibility modelling.

Research Question 2 explored the spatial distribution features and how they vary within identical regions when subjected to different SMA for parks, confirming the regional stability of the SMA process, suggesting that areas with stable outcomes could exemplify regions for further investigation into park spatial allocation. This investigation could, in turn, enhance park planning principles. This highlights the importance for planners and policymakers of understanding the specific deficiencies identified by these assessments in Guangzhou's streets, showcasing the variability introduced by different models, distance measures, and population preferences. Consequently, we advocate for a meticulous selection of variables and methods by policymakers when identifying areas in need before proceeding with specific planning and designs.

Additionally, Research Question 3 compared the different modelling methods with PPA offering a nuanced understanding of parks accessibility. It found that including population preferences in SMA addresses the challenge of defining service radii, a known limitation of these models. Our work revealed that through integrating a population weighted (PW) variable with a network distance (ND) approach, planners can achieve more accurate publicly PPA assessments. This difference in approach highlights the importance of incorporating public perceptions and user characteristics within UGS accessibility modelling. Additionally, the weighting method, weight values, and suggestions for enhancing the precision and stability of SMA presented in this study could be directly or indirectly (depending on the context) integrated with new base models, influence factors, simulation functions, etc. This approach could be employed by future researchers to refine the assessment models of SMA for parks and UGS more widely.

In conclusion, our study underscores the critical role of method selection in SMA for park planning, recommending performing scenario-specific analyses that consider network patterns and population density by integrating demographic data and preference weights, avoiding over-generalisation. Our work offers important guidance for the strategic planning of parks and other UGS.

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