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Discrepancies between perceived accessibility and spatial accessibility modelling: A case study of urban parks in Guangzhou, China

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ABSTRACT

In line with the United Nation's Sustainable Development Goals initiatives across the globe aim to improve access to urban parks. It remains, however, a challenge to accurately measure the spatial accessibility of urban parks. 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 under different SMA approaches for parks confirms the regional differences within 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, aligning more closely with PPA. Particularly, models adjusted for age related differences in travel time preference 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 approach and the need to integrate age related travel time preferences to refine the assessment of urban parks accessibility. It contributes to more accurate and inclusive urban planning strategies.

1. Introduction

In the context of climate change and urban expansion, urban parks have emerged as critical refuges for city residents, providing a range of environmental and cultural benefits that significantly enhance health and well-being. Urban parks 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, particularly when these spaces are within a reasonable distance for residents (Bedimo-Rung et al., 2005; Cohen et al., 2007; Peters et al., 2010; Rugel et al., 2019; Vidal et al., 2021; Akhmet et al., 2023). Recognising their importance, the United

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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 urban parks. This commitment highlights that the accessibility of urban parks is a critical component to be considered in urban policy and planning, ensuring that the benefits of these important green spaces are equitably available to all urban residents.

Accessibility to urban parks is a multidimensional concept that extends beyond mere physical proximity to include how easily different population groups can utilize these areas (Iraegui et al., 2020; Liu et al., 2021). This broader understanding of accessibility is directly linked to broader goals of social equity and environmental justice, but there are many challenges. Accessibility is difficult to assess as it is influenced by a web of factors including land use, transport systems, and individual preferences and constraints (Miller, 2018). For example, children's accessibility to urban parks can be influenced by factors such as safety, parental concerns, and the presence and quality of play facilities (Bekçi, 2021).

Studies typically measure urban parks accessibility through both objective and subjective methods. Traditional objective measures, often obtained through spatial modelling accessibility (SMA), focus primarily on quantifiable spatial characteristics such as distance or travel time. However, they tend to neglect the subjective perceptions of urban residents (Yasumoto et al., 2020). Despite varied methodologies in objective measurements, the reliance on Geographical Information Science (GIS) technology for comprehensive accessibility assessments is widely accepted (Jiang et al., 1999; Neutens et al., 2010; Iraegui et al., 2020). However, a small number of studies have highlighted the variability that the choice of accessibility methods can exert on spatial accessibility outputs and distributions (Budd and Mumford, 2006; Mears and Brindley, 2019). This demonstrates the importance of selecting appropriate measurement methods.

In contrast, population perceived accessibility (PPA) approaches rely on self-reported data that reflect residents' subjective perceptions and emphasise the significant impact of personal preferences, and socio-demographic factors on how accessibility is experienced (Cerin et al., 2017; van der Vlugt et al., 2019). Recent studies have indicated that the outcomes derived from objective spatial measures often diverge from those derived from subjective measures. Research has demonstrated that socio-demographic factors including age, gender, income and mobility can play a role in shaping perceptions of accessibility. This challenges the effectiveness of relying solely on objective or subjective approaches for measuring urban parks accessibility (El Murr et al., 2023; Ma et al., 2022a; Ma et al., 2022b; Sang et al., 2016; Yang et al., 2022). This calls for an integrated approach that considers both objective spatial data and subjective perceptions to provide a more comprehensive understanding of urban parks accessibility.

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 urban park 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 urban park 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 can therefore help inform the strategic spatial development of urban park provision. It has the potential to refine the accessibility of urban planning and design strategies to better match the perceived needs and preferences of urban residents' urban parks.

The remainder of this paper is organised as follows: Section 2 presents a literature review on the various methods used to measure and compares 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 parks accessibility modelling.

2. Literature review

2.1. Introduction to accessibility of urban parks

In the context of climate change and rapid urbanisation, the benefits of urban parks are of considerable importance for residents' physical and mental health (Manandhar et al., 2019; Datzmann et al., 2018; Ghimire et al., 2017). Accessibility is a key precondition for the effective use of urban parks (Kabisch et al., 2016). However, urban parks are often distributed unevenly, leading to heightened scrutiny regarding their accessibility and emphasising their critical role in urban planning (Rigolon, 2016; Mears et al., 2019).

Studies from different urban contexts consistently show disparities in urban park accessibility based on racial, ethnic, and socioeconomic lines. For example, a study in Chicago identifies significant disparities in urban park accessibility among different racial/ethnic and income groups whereby white-majority census tracts enjoy better urban park accessibility compared to minority-dominated tracts (Liu et al., 2021). Additionally, urban parksS in Berlin are unevenly distributed with user preferences varying by immigrant status and age (Kabisch and Haase, 2014). These inequities highlight the need for targeted urban planning to ensure equitable access to urban parks.

The 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 et al., 2019; Datzmann et al., 2018; Ghimire et al., 2017). The accessibility of urban parks significantly influences their use, which in turn impacts physical activity, mental health, and community cohesion (Cohen-Cline et al., 2015; van den Berg et al., 2019). Research shows that easier access to urban parks encourages more frequent visits and longer stays (Lau et al., 2021; Flowers et al., 2016). Conversely, as the perceived distance to these areas increases, usage declines (Soltani et al., 2016).

Planners and local governments are increasingly recognizing the importance of urban park 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, U.S.A. (Steuteville, 2008); the "15-minute community-life circle" in China (Weng et al., 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, 2019); and a 15-minute walking distance from the nearest urban parks for residents in Europe (Stanners et al., 1995). This concept of a "15 min city" has been explored in various contexts in China, including Guangzhou, Shenzhen and Hong Kong in the Great Bay Area, as well as other mainland cities such as Shanghai and Nanjing (Wu et al., 2021; Zhang et al., 2022; Allam et al., 2022; Zhou, 2019).

Whilst a wide range of research provides static measurements of urban park accessibility, they rarely account for the dynamic and mobile nature of humans. Recent studies have sought to address this gap by utilising individual detailed location based information from apps and mobile phones (for example using GPS, mobile signalling, and location-based service data) to measure dynamic accessibility and exposure (for example Kan et al., 2023; Song et al., 2021). These methods can offer a more accurate reflection of real-time status and individual interactions within parks but suffer from their own limitations, such as data representativeness issues and time consuming data cleaning (see Mears et al., 2021).

2.2. *Measurement of spatial modelling accessibility (SMA)*

The term accessibility is widely used in urban planning, transport studies and related fields and encompasses both spatial proximity and perceived ease of access – highlighting the need for a comprehensive approach to assessment (Geurs and Van Wee, 2004). There have been diverse types of measurements for spatial accessibility modelling, depending on the specific purpose of the study. However, on basis of the definition of accessibility, the measurements usually consist of three elements as commonly used within the literature (Radke and Mu, 2000; Wu et al., 2017): 1) people as the demand, (2) urban parks as the supply, and (3) road/walking networks as the physical connection. SMA includes not only physical distance or travel time, but also factors such as transport capacity, distribution of destinations, individual characteristics, quality of destinations, and economic cost of travel. For example, the cost of public transportation can be a significant barrier to accessing urban parks, especially for low-income individuals and families (Basu and Nagendra, 2021). 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. Corresponding specifically to park accessibility, the three key components are residents, parks, and paths, which were not fragmented but mutually restricted and related to each other.

Various methods have been proposed and applied to measure accessibility within urban contexts, each presenting advantages and limitations (Dai, 2011; Dony et al., 2015; Stessens et al., 2017; van Herzele and Wiedemann, 2003; Žlender and Ward Thompson, 2017). However, a single SMA measure often fails to fully capture the service state of urban parks, prompting a shift towards a blend of algorithmic models and spatial processing techniques for a comprehensive assessment of the accessibility of urban parks (Liu 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). 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 and Niemeier, 1997; de Sousa Silva et al., 2018; Rigolon, 2016; 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 et al., 2017; Dai, 2011). 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 and Wei, 2009), Dynamic 2SFCA (McGrail and Humphreys, 2014), Nearest Neighbor 2SFCA (Jamtsho et al., 2015), and Three-Step Floating Catchment Area (3SFCA) method (Wan et al., 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 and 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 and Green, 2008; Cracu et al., 2024). Consequently, employing ND can effectively reduce the overestimations typically associated with SMA assessments (Li et al., 2019; Mears and Brindley, 2019).

2.3. *Population perceived accessibility (PPA) and its comparison with spatial modelling accessibility (SMA)*

While spatial-based measures are extensively employed in assessing urban accessibility, they often fail to adequately consider the individual dimension. PPA includes 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 (Lättman et al., 2018). PPA represents a human- centred evaluation influenced by subjective factors such as personal experience and preferences, in addition to objective factors like distance and park service areas. 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).

Perceived accessibility often differs from calculated measures due to inaccuracies in awareness and subjective evaluations of accessibility components (Pot et al., 2021; Ma, Shi, and Wu, 2023). A study in Hongkong identified no statistically significant relationship between subjective greenspace perception and objective greenspace accessibility, highlighting the importance of perceptions in affecting individual decisions on greenspace usage (Liu et al., 2024). The characteristics of residential populations (such as age and income levels) can 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). Other research has highlighted the disparities between SMA and PPA, such as the differences that emerge for commuting distances (particularly for journeys by train) (Budd and Mumford, 2006; Ryan et al., 2015). 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., 2015; El Murr et al., 2023).

Traditionally, individual perspectives are represented by socio-demographic variables like age, income, and gender, employing a segmentation approach (Titheridge et al., 2010). However, recent studies have highlighted key socio-demographic factors influencing PPA assessment including gender disparities in park access (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 et al., 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 et al., 2011; Pot et al., 2021). By incorporating the characteristics and preferences of diverse social demographics into the planning and design of urban parks, urban planners can promote social justice and equity (Anguelovski, 2016; Rutt and Gulsrud, 2016). In related research the authors identified that of three socio-demographic variables of age, gender and education levels, only age significantly affected the preferred travel time to urban parks in Guangzhou (Ma et al., 2022b; Ma et al., 2024). In this research, it was found that older

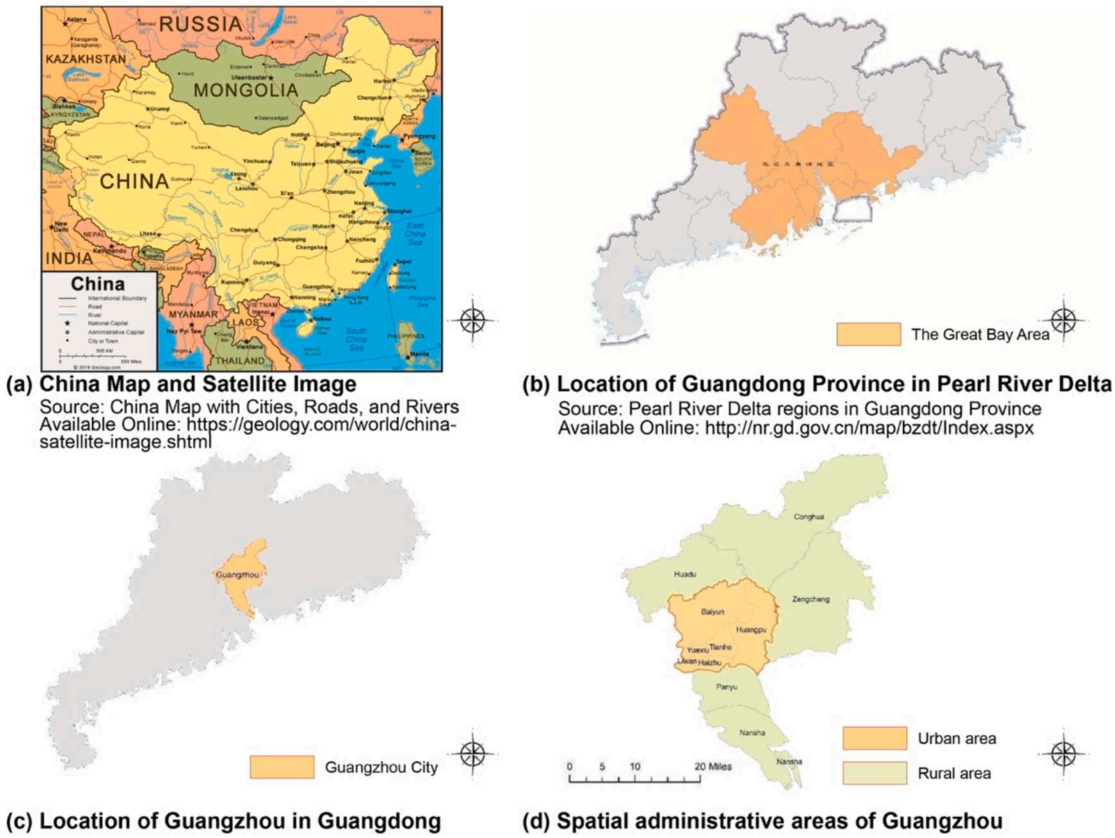

Fig. 1. Location of study area, Guangzhou and administrative district division. (a) China Map and Satellite Image; (b) location of Guangzhou in Pearl River Delta region; (c) location of Guangzhou in Guangdong; (d) spatial administrative areas of Guangzhou.

populations tended to be more willing to spend more time walking to urban parks.

2.4. Literature Gaps and Knowledges Needs

Method selection in SMA for urban parks 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 urban parks accessibility outcomes (Ma et al., 2022a; Ma et al., 2022b). According to the authors' knowledge, no study has directly compared results of eight distinct SMA methods and their spatial distributions (Research Question 1 and 2 within this work) nor examined their differences with PPA (Research Question 3). Identifying the SMA model that most accurately reflects PPA to urban parks is critical, which may enhance the accuracy and equity of urban parks accessibility assessments.

3. Data and methods

3.1. Site Selection: Guangzhou, China

According to the 2020 China Census, Guangzhou ranks among China's seven mega-cities, positioned as the foremost urban centre in southern China and the capital of Guangdong Province (Fig. 1 (a) and (b)). Located at the heart of Guangdong and a key component of the Pearl River Delta (Fig. 1 (c)), Guangzhou is located in one of the world's densest metropolitan areas. The city comprises of eleven districts (Fig. 1 (d)), with six central districts forming the main urban area, including a total of 142 streets (Guangzhou Statistical Yearbook, 2021). In China, a "street" typically refers to an administrative unit that encompasses one or more speciffic neighborhoods. It serves as a basic statistival unit for census data collection and local governance.

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 Urban Green Space 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 urban park accessibility and the need for parks to align with residents' usage patterns and behavioural tendencies.

3.2. Data

3.2.1. 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 socio-demographic information for age, gender, and education level. Gender and education levels were not included in this study as related previous work identified that these did not affect the preferred travel distance to urban parks in Guangzhou (Ma et al., 2022a; Ma et al., 2022b).

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 were 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 and Krosnick, 2009; Kreuter et al., 2008; Dodou and de Winter, 2014), implying the methodological shift in this study likely had minimal impact on the data's integrity.

The secondary data used in assessing park SMA consists of four datasets: 1) Urban parks from OpenStreetMap (OSM) (https://www.openstreetmap.org/); 2) Census data (by age, education, gender) within the streets from the Statistic Bureau of Guangzhou Municipality (open access via: https://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.

3.2.2. 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 ArcMap 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.

3.3. Measurement methods

3.3.1. Eight spatial modelling accessibility (SMA) approaches

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 et al., 2022a; Ma et al., 2022b).

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 and Brindley, 2019). These methods were proceeded 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 weighting, addressing spatial interactions often overlooked in conventional accessibility assessments using buffers and network analysis.

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

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

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.

As outlined above (Table 1), this study enhances the foundational SMA measurement method by incorporating variations in preferred walking time with age, as spatial weights within the spatial model (Preference-weighted Buffer (PWB)). 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 et al. (2022a, 2022b).

$$T_i = \sum\nolimits_{n}^{j=1} \frac{D_j}{DG} \times MT_{D_j} \qquad \text{(Equation 3–3)}$$

whereby Ti indicates the acceptable walking time for residential point i. Dj is the population count of the jst 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 Dj. 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 that was informed by field-survey-derived walking time preferences (see the paper by Ma, Brindley and Lange in 2022 for details). This measurement is in line with distances used in another similar research (Steuteville, 2008; Ayala et al., 2022; Capasso Da Silva et al., 2020).

3.3.2. Population perceived accessibility (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 Fig. 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.

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

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

accessibility, the study employs a 'Satisfaction with the Overall Walking Experience' (SoWEA) indicator, collected via corresponding question in questionnaire survey using a 5-level Likert scale (from 'Very Unsatisfied'- coded as 1 to 'Very Satisfied'- coded as 5). This satisfaction indicator can be seen as a quantified insight into the individual impact of each relevant park spatial feature concerning accessibility. It draws on practices from prior research on PPA in various contexts (e.g., Lättman et al., 2018; Scheepers et al., 2016; Wang et al., 2015), where the self-reported perceived accessibility scale was used for PPA measurement of public transportation, urban parks, and sports facilities − showcasing its applicability in evaluating PPA to parks and other amenities.

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 as illustrated by pie charts (Fig. 3; for full details see Table S2 in the Supplementary Materials) and in each district (see Figure S1 in Supplementary Materials); 2) In relation to Research Question 2 (exploring differences in the spatial distribution of SMA approaches), Section 4.2 investigated the spatial distribution (Fig. 4) and spatial clustering features (Fig. 5) of the 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 spatial modelling accessibility (SMA)

4.1.1. General differences of various spatial modelling accessibility (SMA) outputs

M2SFCA-ND analysis showed accessibility levels closely aligned with those by GB-ND (see Fig. 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 et al., 2019; Mears & Brindley, 2019).

PW2SFCA-SLD analysis indicated more areas of low than high accessibility. Similar to this, the PWB-ND and PW2SFCA-ND models showed higher proportions in poor park accessibility (Fig. 3 (f) and (h)). It suggested that the PW method (that weighted the preferred travel time by age) 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 should be considered as local differences that are more comprehensive, multi-level indicators and broader in its scope of assessment (Porta and Renne, 2005). In addition, previous findings stated that the spatial distribution of parks might not serve certain groups equitably (Guo et al., 2020; Gong et al., 2016), highlighting the need of park planning and assessment that are tailored to the use characteristics and preferences of different socio-demographic factors (Anguelovski, 2016; Rutt and Gulsrud, 2016).

4.1.2. Differences of spatial modelling accessibility (SMA) outputs in districts

The distribution of different SMAs within specific districts can be found in Figure S1 and Table S2 in Supplementary Materials.

4.1.2.1. Differences of spatial modelling accessibility (SMA) outputs within the same districts. The results provided by these figures and tables show that distinct spatial modelling methods exhibit considerable variable performances. Previous research reported by Yang et al. (2022) identified large urban park inequalities in Panyu district highlighting potential disparities with our findings. Yuexiu district has been shown with different performances in SMA by GB-SLD and M2SFCA-SLD. 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 and Han, 2021).

Absolute values tended to be overestimated for SLD compared to ND approaches. 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 et al., 2022), which constrains the connectivity between parks and residents throughout the spatial simulation. The emergence of the area with reduced accessibility, resulting from the foundational shift from the GB model to 2SFCA,

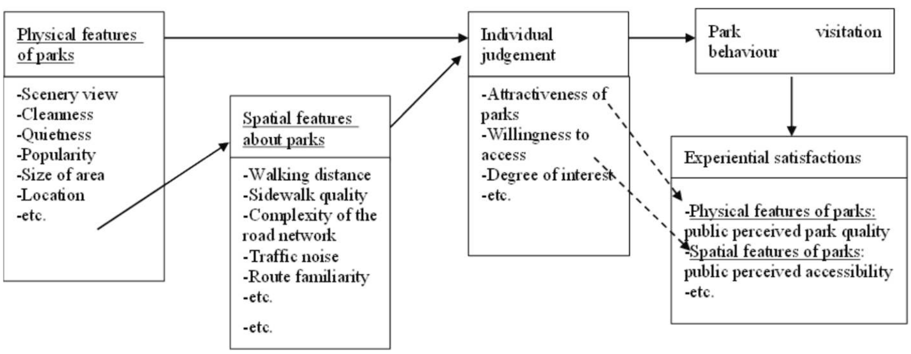

Fig. 2. Conceptual framework of the formation of the public perception on park visitation (Adapted from Ewing et al. (2009, p. 67)).

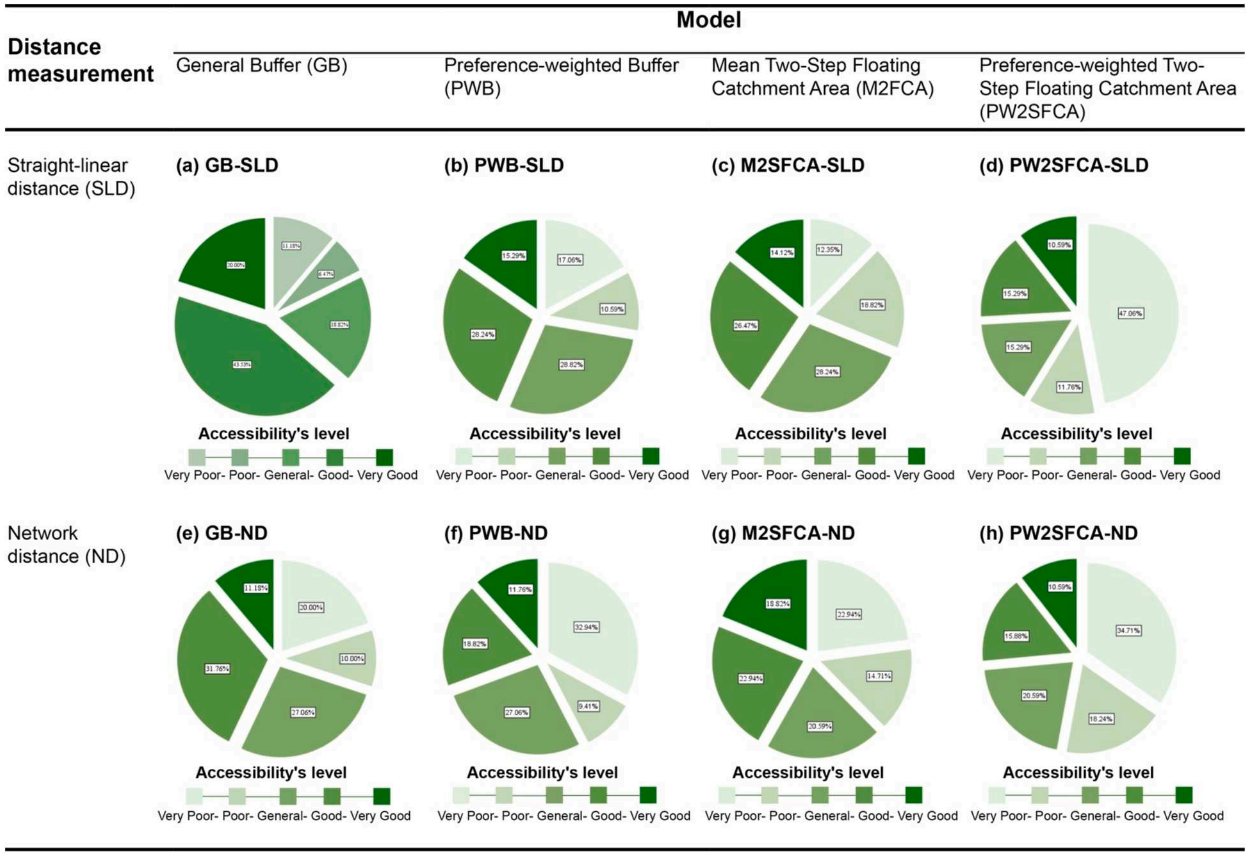

Fig. 3. Distributions of the SMA levels by eight types of models (a-h).

typically indicates a deficiency in the region's attention to the balance between supply and demand for parks (Chen and 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.

The variability in district accessibility levels assessed by PWB-SLD was higher when compared to PWB-ND, but was generally consistent with the other SLD based models. 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.

The limitations of the SLD measure for accessibility modelling was explained by previous research findings that even if parks are in close linear proximity to residential areas, the actual 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 et al., 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.

4.1.2.2. Common issues revealed by spatial modelling accessibility (SMA) outputs within the same districts. One of the outcomes of this work is the policy suggestions that can potentially help improve park accessibility in Guangzhou. These suggestions focus on the common issues repeatedly identified by different modelling approaches within the same area, or those that do not conflict across models. For example, work showed that the Tianhe district exhibited lowest park accessibility by PWB-ND, a significant decline from the other approaches (see Table S2 in Supplementary Materials). This stark contrast highlighted the influence of regional population composition on park accessibility outcomes. Conversely, the Panyu district maintained high accessibility with over half of areas rated as 'Very GoodAccessibility' (see Figure S1 (f) in Supplementary Materials). 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 et al. (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 the 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

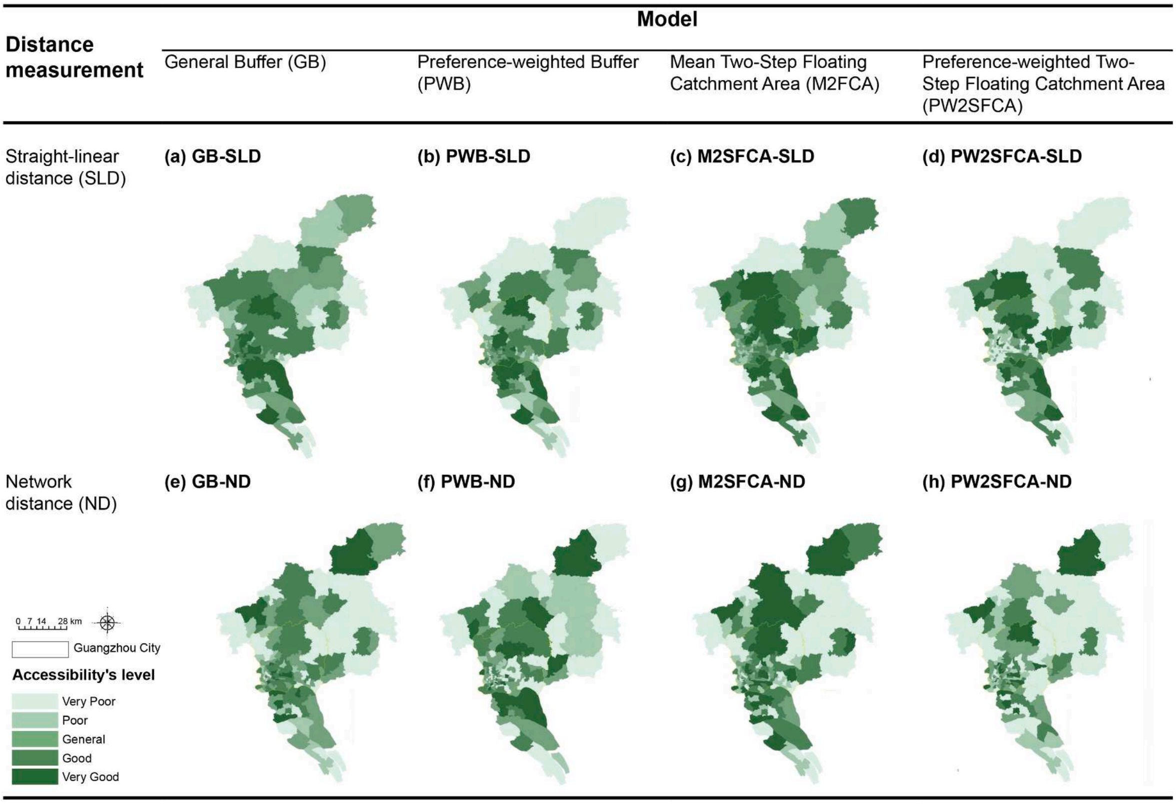

Fig. 4. A summary on spatial distributions of SMA levels evaluated by eight models (a-h).

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 district had the lowest accessibility level using the PW2SFCA-ND model (see Table S2 in Supplementary Materials). The ND spatial metric highlights the poorest accessibility in the centre city, suggesting an urgent need for road network improvements in the inner city area, especially Huangpu and Tianhe, to enhance park accessibility. However, Tianhe had a higher prevalence of 'Very Good Accessibility' streets (see Figure S1 (h) in Supplementary Materials), marking the disparity in urban infrastructure and planning across the streets in this district (Yang et al., 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 urban parks 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 spatial modelling accessibility (SMA)

This section, in line with Research Question 2, explores spatial patterns at a sub-district level.

4.2.1. Spatial distributing features of unweighted spatial modelling accessibility (SMA)

The GB-SLD analysis revealed 'Very Poor' park accessibility predominantly at urban fringes (Fig. 4 (a)) and 'High-High' clustering in the city centre – indicating uniformly high accessibility (Fig. 5 (a)). Clusters (most of 'Low-High' and 'Low-Low' ones) in suburban areas 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 Fig. 4 (a) and (c)) Both approaches ignored the effect of road network structure, which connects infrastructure and residents in reality and 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).

GB-ND (Fig. 4 (e)) and M2SFCA-ND (Fig. 4 (g)) park accessibility distribution highlighted that 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. It indicates that 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 and Brindley, 2019).

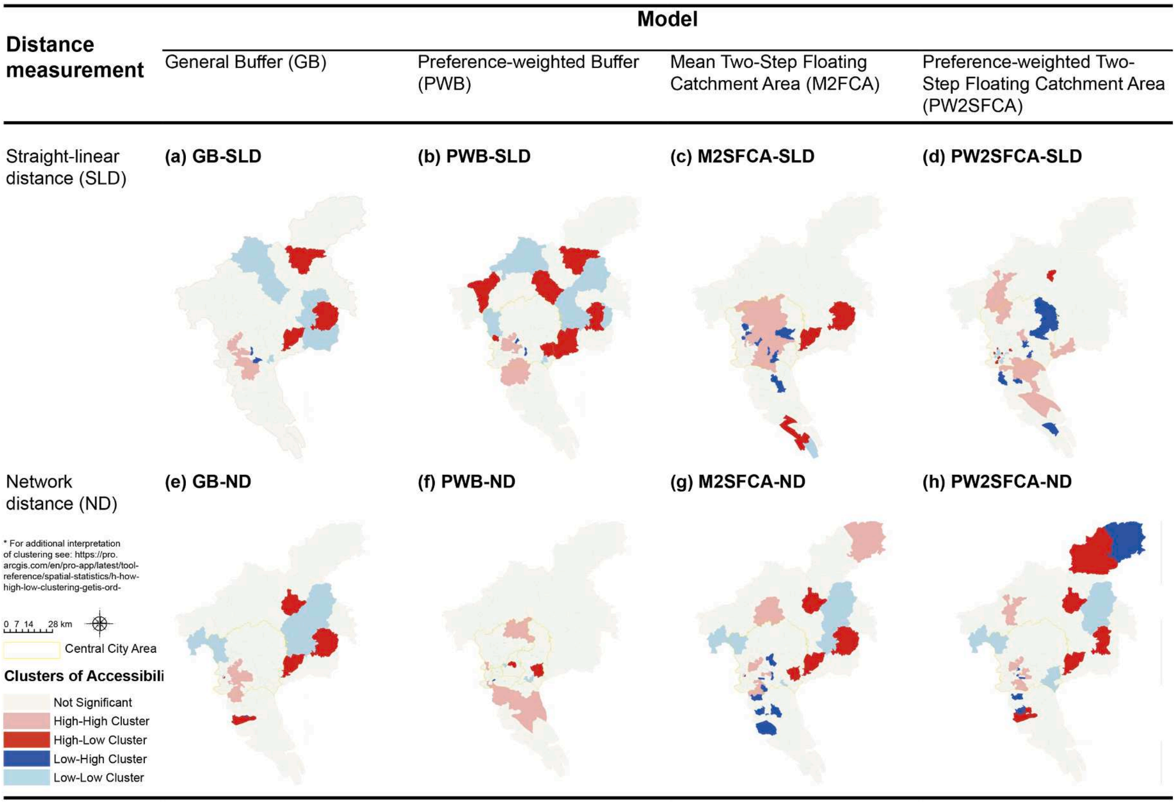

Fig. 5. A summary on spatial clusters of eight types of SMA (a-h).

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.

To conclude, the consistent findings across four SMAs employing non-weighted walking distances, as discussed above, 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 Ghamsary et al., 2023).

4.2.2. Spatial distributing features of preference-weighted spatial modelling accessibility (SMA)

PWB-SLD 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 ((Fig. 4 (b) and Fig. 5 (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 (PW) age related walking time preferences 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. Previous studies have also highlighted the need to include age within accessibility assessment. For example, Yang et al., (2022) revealed the elderly were more likely to perceive poorer accessibility than younger generations. Therefore, in contrast to the unweighted GB-SLD's less varied accessibility across streets (Fig. 5 (a)), the incorporation of population's preferences (that varies in space) enables PWB-SLD park accessibility to exhibit higher spatial variation.

PWB-ND (Fig. 4 (f)) differed from PWB-SLD and GB-ND and identified significant park accessibility deficits concentrated in the central city's Mideast and East. This showcases the pronounced influence of road networks and population preferences on accessibility evaluation. Additionally, 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 urban parks distribution (Yang et al., 2022).

Instead of preference weighting methods, analyses utilising the ND spatial metric (as shown in Fig. 4 (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 urban parks accessibility and consequently require increased attention (Mears and Brindley, 2019).

4.3. Discrepancy between spatial modelling accessibility (SMA) and population perceived accessibility (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.

4.3.1. Overall comparison

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 2, which quantifies the alignment between SMA and PPA through differential values.

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. 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 et al., 2021). Furthermore, among five analysed SMA configurations (PWB-SLD; M2SFCA-ND; M2SFCA-SLD; GB-ND; GB-SLD), there is a noticeable tendency for SMA to overestimate accessibility compared to PPA. This observation supports the findings of previous work that SMA tended to overestimate the PPA (e.g., Ryan and Pereira, 2021; El Murr et al., 2023).

The most notable discrepancy between SMA and PPA was observed with the application of the GB method, particularly when employing the ND measure. 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 and 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. This approach also presented a more balanced distribution between underestimation and overestimation of PPA by SMA. 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 et al., 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.

4.3.2. Differences between spatial modelling accessibility (SMA) and population perceived accessibility (PPA) based on choice of modelling method

Furthermore, this study highlights how incorporating age (due to its influence on preferred walking time) into the modelling improves the correlation between spatial assessments and PPA (see Table S3 in Supplementary Materials for details). The result

Table 2
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

corroborates the necessity of incorporating population preference variables in SMA simulations (Pot et al., 2021; Tan et al., 2022) and their effectiveness in aligning with PPA. Regarding the 'Basic modelling method' factor, our study 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 PW travel distance (weighted by age related preferred walking time). The discrepancies in the assessment of accessibility extents (including the variations in over- or under-estimations relative to PPA in Table 3) revealed that spatial assessment models, which do not incorporate population preference attributes to modulate travel time/distances, exhibit a propensity towards overestimating accessibility. This trend was notably more pronounced when contrasted with PPA, which is inherently subjective and perception-driven. They hereby suggest that the overestimation of park accessibility by SMA with unweighted variables, in comparison to PPA, seems hard to be alleviated 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 et al., 2011; Ma and Cao, 2019).

Notably, a potential strategy to diminish the discrepancy—predominantly overestimation—between SMA and PPA, is 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 Preference Weighted (PW) walking time (incorporating age related preferred walking time weighting) in four assessment models resulted in a general trend where park accessibility, as determined by these models tended to underestimate PPA. This discrepancy between SMA and PPA was less pronounced when introducing the PW method, exhibiting a smaller range in mismatch occurrences, as opposed to that within the 'Unweighted' method. Consistent with the results from Lättman et al. (2016b), this finding confirms 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.

Notably, the integration of PW travel time alongside the ND spatial metric, particularly within the newly developed PWB-ND approach significantly reduces the mismatch between SMA and PPA outcomes. This appears to contradict the prevailing view that the 2SFCA model is more advanced than the traditional GB model in SMA simulations (Tao et al., 2020). This suggests that if the objective of spatial accessibility simulation is to diminish the deviation of SMA from PPA, employing a combination of PW travel distances, the GB model, and the ND spatial metric constitutes a more effective strategy, rather than indiscriminately adopting so-called "more advanced" foundational models.

5. Conclusions

5.1. Limitations and future research

In this paper, we have undertaken 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 in 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, this study did not consider factors such as park type, popularity, quality, size, and internal facilities, which may affect park's attractiveness to different populations, physical service radius, and perceived accessibility. The correlation between these characteristics and park service range should be quantified as weights or variables in SMA through detailed investigation, which could be an interesting direction for future research. However, this is beyond the scope of this study, which focuses on analysing the differences between general spatial accessibility and perceived accessibility, as well as the fit of different modelling approaches to perceived accessibility.

It should also be acknowledged that advanced big data collection methods can provide geographically-based park service data with greater timeliness and spatial resolution. These methods include GPS data, mobile signalling data, and location-based service data (e.g., Kan et al., 2023; Song et al., 2021; Mears et al., 2021). Future research could integrate these real-time, dynamic spatiotemporal data into spatial and perceptual accessibility models, thus exploring the spatiotemporal characteristics of their differences.

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 modelled outputs, 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 age related walking time preferences 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

Table 3
Impact of demographic preference weights of travel distance on the extent of SMA assessment diverging from the PPA.

Element	Method	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	

models demonstrate 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 urban parks accessibility modelling.

Research Question 2 explored the spatial distribution features and how they vary within identical regions when subjected to different SMA for parks. Although findings confirmed the regional differences of the SMAs of urban parks, a few areas with stable outcomes from different SMA measurements could exemplify regions for further investigation into the spatial allocation of park provision. 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 park 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 urban parks accessibility modelling. Additionally, the weighting method, weight values, and suggestions for enhancing the precision and stability of SMA presented in this study could be 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 urban parks and urban green space 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 urban parks and other urban green space.

CRediT authorship contribution statement

Yueshan Ma: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paul Brindley:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Rui Wang:** Writing – review & editing, Writing – original draft, Visualization, Project administration. **Eckart Lange:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tra.2024.104292.

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