smart cities

Article

Public Vitality-Driven Optimization of Urban Public Space Networks—A Case Study from Nanjing, China

Ning Xu [1,2,*], Xiao Zhang [1,2] and Pu Wang [1,2]

[1] School of Architecture, Southeast University, Nanjing 210096, China; 220220274@seu.edu.cn (X.Z.); 230248015@seu.edu.cn (P.W.)
[2] Jiangsu Provincial Urban and Rural Digital Technology Engineering Center, Nanjing 210096, China
* Correspondence: 101011755@seu.edu.cn

Highlights:

What are the main findings?

- Nanjing's public spaces are unevenly distributed, with areas of high vitality predominantly concentrated in the urban center.
- Enhancing connectivity between public spaces is crucial for improving overall vitality.

What is the implication of the main finding?

- Applying circuit theory to simulate the development needs of public vitality in order to enhance the connectivity of public space networks.
- An optimized path for vitality-driven public space network systems was provided from a human-centric, bottom-up perspective.

Abstract: Spontaneous recreational activities in public spaces are a vital source of public vitality. Given the similarity between the walking patterns of recreational crowds in public spaces and the movement of electrons on a two-dimensional circuit surface, this study combines big data from various sources to create an "electrical conductivity surface" that attracts and aggregates recreational crowds. Using current flow simulation, we generate the path selection preferences of people as they move across public spaces. The results reveal an uneven distribution of public spaces in Nanjing's main urban area, with high-vitality areas mostly concentrated in the urban center. The core demand for enhancing public vitality lies is improving connectivity between multiple spaces. Based on this, the public space plan for Nanjing's main urban area emphasizes overall connectivity by aligning with the natural landscape, thus linking the city's green and gray infrastructure. In this study, we have assessed current public space services and their development potential from a number of different angles, developing a digital approach for optimizing the urban layout. We aim to provide a human-centric, bottom-up perspective to complement the top-down city planning and management approach. This will enable urban planners to make informed decisions for creating and managing more vibrant cities.

Keywords: public space; public vitality; circuit theory; spatial optimization

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1. Introduction

With the continuous growth of the global population, an increasing number of people are choosing to migrate to cities in pursuit of a better quality of life and more job opportunities. As part of this process, cities need to not only focus on improving economic and social standards, but also to pay attention to creating a suitable living environment for their citizens [1]. Urban vitality is as an important indicator for measuring the effectiveness of urban construction, and is a key factor in reflecting the healthy development of cities and the stimulation of positive social momentum [2]. It represents the vitality and activity level of a city or a specific area. In this study, urban public vitality refers to the intensity, diversity, and interaction of human activities within urban spaces; these can be directly observed through interpersonal communication, urban life, and other interactive activities. Urban public spaces are key sources and the means of regeneration of urban public vitality, playing an irreplaceable role in promoting community interaction and enhancing urban attractiveness [3]. Urban public space refers to open spaces accessible to the public and used for daily life and social activities, and includes urban squares, streets, parks, and other outdoor spaces [4].

How is urban public vitality generated? Researchers have proposed a number of different insights that have had a wide-ranging impact. Alexander argues that urban vitality is the natural result of the interaction between individual construction behaviors, forming general rules at a larger scale [5]. Sorkin emphasizes that the introduction of urban vitality requires not only reducing the ubiquitous practice of authoritarian design, but also incorporating numerous independent starting points [6]. Gehl claims that the accessibility of urban public spaces and the connectivity between different areas can promote social interaction among people, thereby improving urban vitality [7]. The creation of urban public vitality is actually a result of multiple factors working together. High accessibility and good connectivity are the foundation of public vitality. Diversified functions and inclusive public spaces help attract different groups of people, while vibrant commercial and cultural activities, as well as social interactions, help to enhance social vitality. The key is to create a multifunctional space with high connectivity, one which is suitable for bringing people together and promoting interaction, allowing public spaces to truly become the center of urban life.

Accordingly, in order to effectively promote the concept of urban vitality, a public space network system needs to establish a set of minimum adjacency standards for urban spaces, and to apply these standards universally to all areas transitioning towards more vibrant urban places. In this way, full connectivity can be achieved within the network. By introducing a series of smaller public spaces to connect to the larger ones, the walkability of the network can be significantly improved. This not only increases the range of recreational activities for citizens between and within different public spaces, but also increases people's motivation to participate in urban life [8]. The movement of these crowds, combined with the heterogeneous landscape of the public spaces themselves, continuously injects vitality into a city [9], thereby improving the overall service of the public space system [10], subsequently having a positive impact on society as a whole [11–13].

Due to limitations in technical approaches, traditional urban public space research has mostly focused on a specific urban area or segment at the meso- or micro-scale. With the development of digital technology, the application of mobile phone signaling, POI data, and social media check-in data has provided tools for accurately identifying and tracking users of public spaces, promoting large-scale studies [14]. However, current research on public space vitality primarily focuses on using multi-source data to assess vitality [15,16], or on exploring the different factors that influence spatial vitality [17], and proposing relatively subjective design principles or management strategies based on this [16]. In terms of the optimization of public spaces, most studies focus on the accessibility gap faced by urban residents in terms of supply and demand, and on means of improving the user friendliness of the layout by adding new public space locations [18]. In general, current research lacks a systematic exploration of quantitative optimization methods for public space networks from a structural perspective. Nonetheless, contemporary smart cities aim to achieve more scientific development, more efficient management, and a better quality of life. This not only needs improved economic and social development through intelligent infrastructure, but also requires full use of big data technology to gain a deeper understanding of people's needs, in order to create a more personalized living environments [1], thus optimizing public services and promoting the intelligent transformation of urban morphology.

Although the connectivity of public spaces has received significant attention in recent studies [19], a lack of effective assessment methods has meant that most existing research has primarily focused on the connectivity layout of micro-level public spaces by means of field surveys. There has been very little analysis of public space connectivity on an urban scale. Public spaces are specific "patches" within a city, and have distinct similarities with ecological patches in terms of their distribution within an urban space. The connectivity analysis method for ecological patches focuses on macro-scale network characteristics and can serve as a reference for the pathways within a public space network. Among the existing methods, the circuit theory proposed by McRae predicts and simulates the flow behavior of objects using a "random process". Within a circuit, the movement of charge is random, and the movement of organisms in nature exhibits similar characteristics. Circuit theory analysis compares biological entities to electric charges, and the influence of the environment on the movement of organisms is set as corresponding electrical resistance, thus simulating the movement of organisms within the environment. This not only greatly reduces the model's calculation load and required conditions, but also enables accurate and robust predictions for large-scale heterogeneous environments. This coincides with new urbanism's methods for organically generating rules at a larger scale through individual forms of construction behavior [5]. The current circuit theory simulation shares similar random walk characteristics with ecological flow, allowing it to be widely used in the creation of ecological networks [20] and the analysis of movement patterns of individuals and gene flow in heterogeneous landscapes [21]. This study applies circuit theory to simulate the organic interaction between recreational crowds in urban public spaces, enabling a systematic examination of their layout and function from a macro-scale perspective. An optimization method for a complex public space network is then created based on structural and functional considerations. Circuit theory can generate flow paths with hierarchical structures. These allow for the digital quantification of results to improve the accessibility of existing isolated public spaces, and can integrate and activate particular blocks to improve their service levels.

To fill the research gap in the optimization of urban public spaces, this study combines and categorizes multi-source datasets, simulating demands from the perspective of public vitality development using circuit theory software Linkage Mapper v 3.1.0. Toolbox and Circuitscape v 4.0.7. It then generates an optimization plan for a suitable system based on demand assessment combined with the current layout of urban public spaces. The aim is to provide a scientific basis for the systematic optimization of public spaces, promoting high-quality urban development and improving people's well-being. The research objectives include:

- Creating a digital approach for optimizing urban public space systems by integrating the assessment of current services and development potential;
- Determining a suitable application of circuit theory to the simulation of urban public vitality development needs, and establishing a circuit theory simulation based on the activity characteristics of recreational crowds within the public space system.

2. Methods

Based on a combination of public space datasets, this study evaluates the current vitality of public spaces using multi-source information data. It then simulates the movement of electrons as "recreational crowds in urban spaces" using circuit theory, generating paths that connect public vitality. Finally, current land-use data, public space vitality assessment, and development needs are combined to propose a public vitality-driven urban public space system planning method, which emphasizes integration and connectivity (Figure 1).

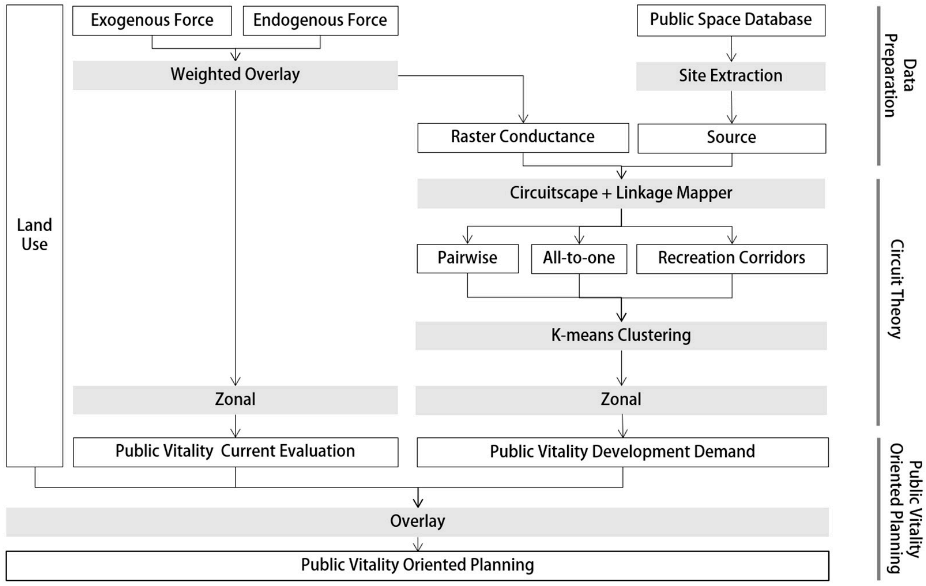

Figure 1. General technical method.

2.1. Construction of an Urban Public Space Dataset

Urban public spaces include squares, streets, green spaces, street frontages, markets, and other pedestrian areas. Since the existing urban land classification in China does not feature public spaces as a land-use type, its spatial boundaries are relatively ambiguous and need to be determined based on available literature, field surveys, land-use types, and spatial morphology. Various types of public spaces, such as squares, green spaces, streets, and historical and cultural spaces, are extracted from multi-source data, excluding ecological protection green spaces. By combining current land-use status with field surveys, the distribution of these spaces can be determined, and an urban public space dataset is constructed (Table 1).

Table 1. Data sources for urban public spaces.

Primary Type	Secondary Type	Not Included
Green Space	Park Waterfront Space	Ecological Water Reserve
Square	Square	
Composite Block	Commercial Block Living Block	
Street	Walking Space Pedestrian Zone	

2.2. Evaluation of Current Public Vitality

Urban public vitality is brought about by people, and is stimulated by the interaction between specific spaces and the synergy between existing built elements and interpersonal interactions within the city. In urban public spaces, the presence of recreational crowds reflects the psychological need for social interaction as a collective biological species, meaning that the distribution of crowds can trigger internal motivational behavior for communication between individuals, creating an endogenous force. At the same time, the existing built elements within the city provide a material carrier for these interactive activities, forming an exogenous force. Therefore, the distinction between endogenous and exogenous forces means that the mechanism of urban public vitality can be divided into subjective human-centered influences and objective environmental factors.

Exogenous forces refer to objectively existing urban environmental conditions that influence the movement of recreational crowds, including transportation facilities and service facilities. The accessibility of public transportation facilities, such as bus stops and subway stations, in the vicinity of public spaces is the foundation for maintaining their vitality. High-capacity public transportation can increase the frequency with which people travel medium and long distances to visit these spaces. The accessibility of high-level public spaces is largely determined by public transportation, especially in high-density cities that advocate bus priority and green travel. The distribution of service facilities is also of significant reference value when studying recreation-oriented crowds [22]. Service facilities such as shopping, dining, daily living, education and culture, public amenities, sports, and leisure facilities located around and within public spaces can provide functional diversity, support public life, and stimulate vitality [8].

Endogenous forces describe the subjective willingness of recreational crowds to move to specific areas based on factors including information acquisition and crowd aggregation. From the social observations proposed by William H. Whyte and Jane Jacobs [3,23], to the rise of Instagram-friendly locations following the advent of digital media networks, all of them reflect the fundamental need for social interaction. It is this need that stimulates the generation of urban vitality from the individual's inner drive. By collecting information generated by individuals as they move, their subjective flow tendencies can be revealed. Endogenous forces can be divided into two subcategories: social media check-ins and mobile signaling data. These two categories reflect the vitality of public spaces from the perspectives of recreational individuals' subjective intentions and their actual behavior. Specifically, social media check-in data focus on revealing the information sharing and receiving process of recreational individuals, reflecting their interest and social interactions within specific spaces. On the other hand, mobile signaling data capture the trajectories of recreational individuals as they move through real-world locations, further depicting their mobility and aggregation trends within the urban spaces. Compared to traditional spatial indicator methods based on grids or census areas [24], a combination of both methods can provide real-time insights into crowd movement and changes in vitality, thus revealing dynamic patterns in different time periods and scenarios, and capturing behavioral intentions and social interactions. This can more directly reflect the influence of micro-environmental factors on urban vitality.

After determining the various factor types, an Analytic Hierarchy Process (AHP) is adopted; this features an expert scoring system to evaluate the weights of the different factors. The vitality of existing public spaces influences the movement of recreational crowds from both exogenous and endogenous perspectives, and therefore directly serves as the conductivity surface for subsequent calculations within the circuit theory. At the same time, zonal operations are conducted to obtain an evaluation of current public vitality, providing a basis for the final planning outcome (Figure 2).

Based on the Amap POI classification system, this study combines 29 sets of three-level classification data closely related to exogenous forces, extracting 5 transportation facility factors and 8 service facility factors according to industry distinctions (as shown in Table 2). When constructing an activity model for recreation-oriented crowds, these categories are closely related to residents' daily lives and directly promote local recreational activities.

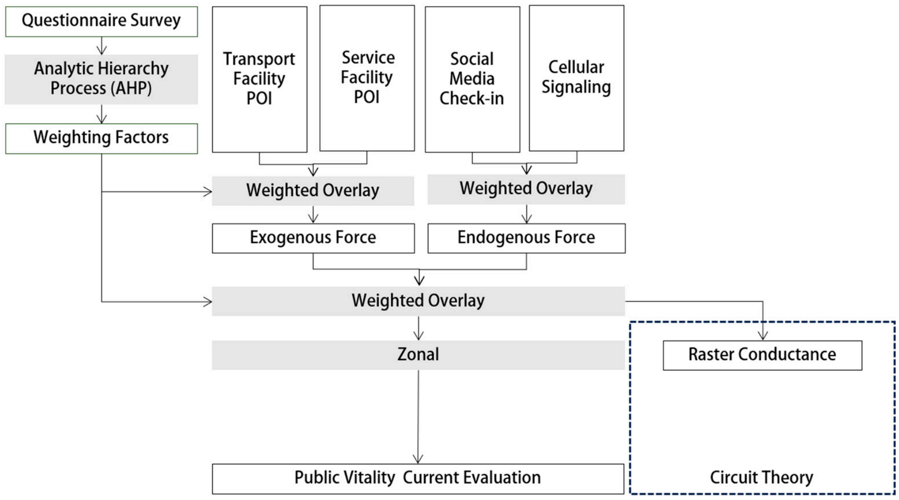

Figure 2. Technical method for current public vitality evaluation.

Table 2. Classification of exogenous force factors.

First Factor	Secondary Factor	Tertiary Factor
Transportation Facilities	Metro Station Ferry Bus Stop Railway Station Coach Station	/ / / / /
Service Facilities	Shopping	Mall Grocery Supermarket Bird and Flower Store Market Business Street
	Catering	Chinese Restaurant Western Restaurant Cafeteria Casual Dining Cafe Tea House Bakery Dessert
	Living	Shared Power Bank
	Utility	Newsstand Toilet
	Sports and Leisure	Sports and Leisure Gymnasium Entertainment Venue Sanatorium Leisure Service Theater
	Scenic Zone	Tourist Attraction Park Plaza
	Culture	Museum Exhibition Hall Convention Center
	Residential	Community Center

2.3. Evaluation of Public Vitality Development Demands

Circuit theory abstracts site conditions into a two-dimensional circuit surface. Public space patches with higher service levels can be treated as sources, i.e., input and output points for current flow. During the simulation, different resistances are assigned to spatial grids in order to influence the magnitude of the current formed by the random movement of electrons. The resulting current magnitude predicts the trajectories of the simulated objects, with areas of higher current indicating preferred paths for these simulated objects. The conductance value is the reciprocal of the resistance, with both having the same effect on electron movement [25]. Existing studies tend to use factors that are unfavorable to the random movement of electrons in order to construct a "resistance surface" for creating ecological networks [26,27]. If we reverse the thinking and set the recreational crowds in public spaces as the simulated objects, and consider that the movement of crowds in highly built environments is mainly influenced by the driving force of flow, we can use a "conductivity surface" composed of different factors that attract electron movement for evaluation.

Circuit theory calculation requires source selection and conductivity surface creation. The sources of public vitality are the starting and ending points of the random movement of large numbers of recreational crowds. Taking accessibility of public spaces as the selection criterion, spaces with a bus stop within 300 m and those with a subway station within 500 m are selected as sources. The factors required for constructing the conductivity surface must support and promote residents' recreational activities in these urban spaces. These consist of exogenous conductivity factors, composed of transportation and recreational service facilities, and endogenous conductivity factors, stimulated by the presence of recreational individuals (Figure 3).

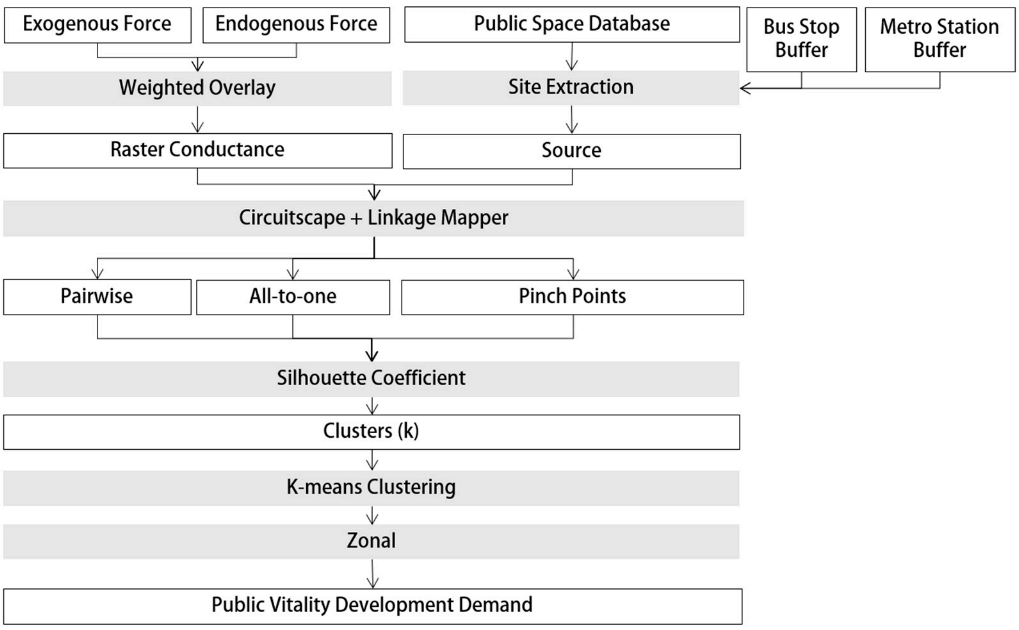

Figure 3. Calculating public vitality connectivity demands using circuit theory.

By combining various models for circuit theory analysis, it is possible to fully evaluate the simulation results of both the overall system and those obtained within corridors, thereby creating a suitable development assessment system. Among these, the many-to-one model reflects the differences in current intensity between different corridors in the overall system network, i.e., the overall potential connectivity of the system. The pairwise model evaluates the status within the corridors, i.e., the differences in connectivity within the spaces of each corridor. Pinchpoint analysis anchors important connection nodes within the corridors, identifying key maintenance spaces to realize corridor functions [20]. Circuit theory analysis is performed using Linkage Mapper and Circuitscape. This analysis sets the maximum distance of electron flow to limit the movement of the simulated objects, thereby influencing the results. Related studies show that the average maximum distance that Chinese adults walk is approximately 15,000 steps [28]. Combined with the average step length, the maximum route length covered by recreational crowds is thus set to 10,000 m.

By running the K-means clustering algorithm in Python, the development demand for public vitality is identified, and different demand clusters with varying levels of intensity are classified. Cox-box transformation and z-score standardization are applied to the data to ensure clustering accuracy, while the Silhouette Coefficient method is used to evaluate the clustering effect and calculate the number of target clusters (k) under the condition of the highest average silhouette coefficient.

Based on zonal analysis on the ArcGIS platform, the connectivity demand paths for public vitality are mapped to specific urban zones, revealing data differences in the development demand for public vitality between various zones, which in turn drives the generation of more scientific urban public vitality development plans.

2.4. Public Space Planning

To drive urban development towards the ultimate goal of smart cities, it is essential to manage and plan the urban public space network system in a sustainable manner. By integrating the evaluation of the current status and developmental requirements for public vitality, the existing public space pattern can be supplemented, adjusted, and connected from a spatiotemporal perspective. Based on the current layout, and considering both the vitality development demands and the difficulty of improvement, urban public space network planning is divided into pilot areas and long-term development areas, forming a gradual planning approach driven by public vitality.

3. Study Area and Materials

3.1. Study Area

The main urban area of Nanjing, Jiangsu Province, is selected as the study area. This covers a total area of approximately 303 km^2, and includes Gulou District, Jianye District, Xuanwu District, Qinhuai District, Yuhuatai District, and parts of Jiangning District and Qixia District (Figure 4). Due to the inherent uncertainty in the flow of electrons within circuit theory, the movement of electrons is hindered at the boundary of the study area where their directions are constrained, leading to a significant boundary effect. Therefore, a 3 km buffer zone [25] is delineated to eliminate the influence of this effect.

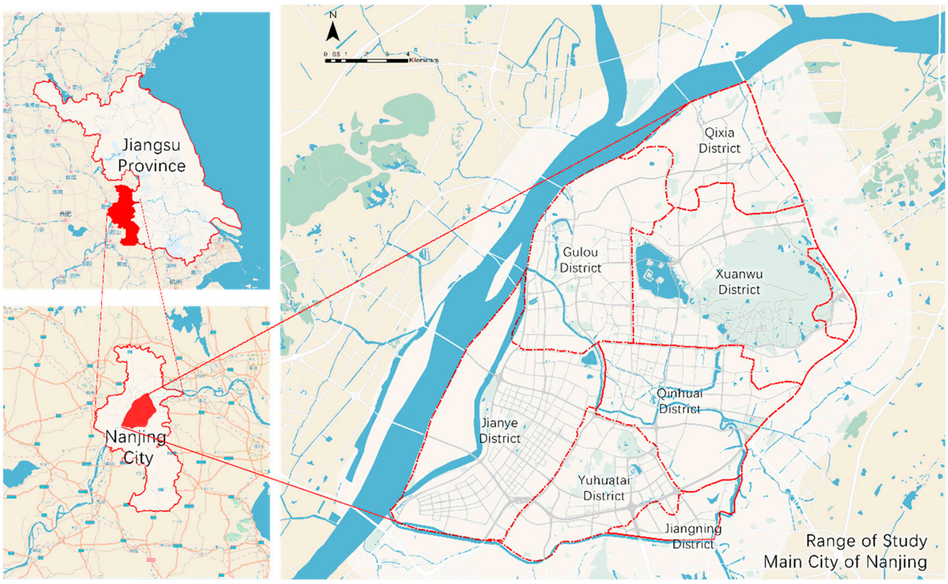

Figure 4. Study area.

3.2. Data Sources

The data used in this study include the following: multispectral satellite images with a 5 m resolution taken by the Chang Guang Satellite "Jilin-1" Wideband 01A in September 2022, Nanjing Urban Master Plan (2011–2020), Nanjing Land Use Master Plan (2006–2020), Nanjing Main Urban Area Public Space Plan, and Nanjing Historical and Cultural City Protection Plan (2010–2020). Combined with Baidu Street View maps and extensive field surveys, the current distribution of public spaces in Nanjing's main urban area was identified.

In February 2022, POI data scraped from the Amap Open Platform https://lbs.amap.com/ (accessed on 12 February 2022) were used to select and organize transportation facility POI and service facility POI data related to the study. Python was used to scrape Sina Weibo social media datasets from 10 February to 11 March 2022, which included all POI spatial locations where users checked in at tourist spots and the number of check-ins. The mobile signaling data for the entire period of holidays, weekends, and weekdays from 1 October to 31 October 2022, were calculated and organized.

4. Results

4.1. Current Distribution of Public Spaces

There are a total of 1052 public spaces in Nanjing's main urban area, covering an area of 35.58 km^2, and accounting for 11.67% of the total study area. According to the recommendations of the World Health Organization [29], 9 m^2 of green space should be provided for each resident of a city. With a resident population of 4.6 million, Nanjing's main urban area should provide at least 41.58 km^2 of green space for the public. Expanding this to include squares, streets, and other areas would require an even larger total area, indicating that the existing public space in the study area is seriously insufficient. The largest public space is located on the eastern side of the study area, accounting for 39.68% of the total public space; there are 516 small public spaces (less than 1 acre in size) [30], making up 49.05% of the total number and 2.52% of the total area. This suggests that there is a significant disparity in the sizes of public spaces within the central urban areas of Nanjing, with smaller public spaces being more prevalent. Small-scale public spaces are limited by their size, which leads to issues such as a limited service population and a single-functionality design. However, these spaces are often located in highly accessible areas, resulting in higher usage by local residents. From a morphological perspective, the distribution of public spaces in Nanjing's main urban area is uneven, forming a well-connected network only in certain areas, while other areas suffer from insufficient allocation, or even a complete absence of public space (Figure 5).

The difference in scale of these public spaces has a significant impact on urban vitality. Large spaces provide flexibility and capacity for large-scale social interactions, while small spaces play an important role in offering easily accessible spaces for people on a day-to-day basis. To foster a vibrant and inclusive urban environment, it is essential to balance the allocation of space types based on considerations of function, accessibility, and equity.

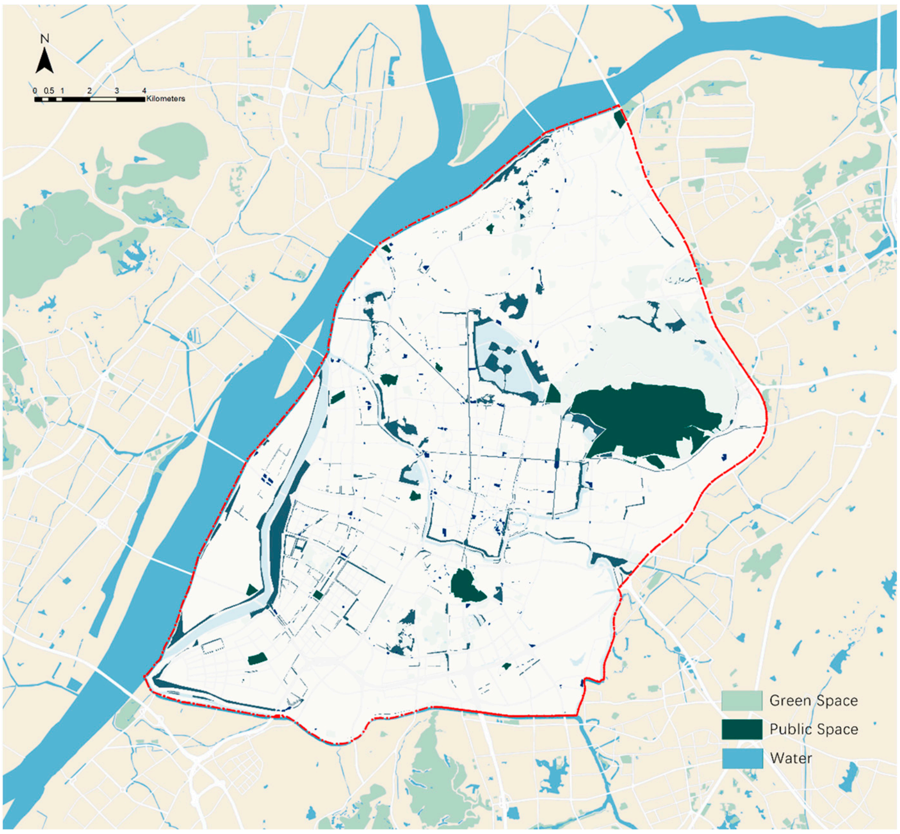

Figure 5. Current distribution of public spaces.

4.2. Evaluation Results of Current Public Vitality

4.2.1. Factor Weights and Their Impact

Within the evaluation factors for the current public vitality in Nanjing's main urban area, the weighting for catering (0.035), sports (0.030), and shopping (0.024) are higher than other service facility factors. The corresponding business formats related to these factors have a more direct positive effect on enhancing the current public vitality of the study area. The weighting of transportation facility factors (0.271) is higher than that of service facility factors (0.174), indicating that transportation has a greater effect on promoting the movement of recreational crowds. Compared with services, which are more effective in attracting recreational crowds to stay, transportation has a more prominent influence on enhancing vitality within the study area. For mobile signaling data, both daily and holiday population data play equally important roles in maintaining urban public vitality (0.220), while Weibo check-in data, due to platform audience and manual operation limitations, only serve as auxiliary information sources for calculating endogenous factors (0.116). The combined weight of endogenous forces (0.555) is higher than that of exogenous forces (0.445), indicating that the stimulation of public vitality by recreational crowds relies more on endogenous forces generated by interactions and communications between people, rather than on exogenous forces provided by the site and surrounding built facilities.

4.2.2. Distribution Characteristics of Exogenous Forces

Specifically, the spatial distribution characteristics of the kernel density of various service facility POIs constituting exogenous forces are different, meaning that the vitality distributions they represent are not the same. Compared with the service facility POIs, the distribution of transportation facility POIs exhibits a more distinct cross-shaped strip structure, resulting from the layout of main roads and important subway stations. All factors show high kernel density in the center of the study area, indicating good vitality in the city center. This characteristic is more prominent in the overall kernel density map of service facility POI factors, which reveals the centralized nature of public vitality in the study area. At the same time, two secondary high-value areas are distributed along the main urban roads surrounding the core area to the south and northwest, while mountainous areas and water features generally show lower values, indicating the current low level of service facilities in natural areas within the study area.

4.2.3. Distribution Characteristics of Endogenous Forces

Endogenous forces are mainly represented by mobile signaling data taken from daily and holiday visitors. The common feature is that the distribution of recreational crowds is significantly higher in built-up areas than in natural landscapes, with a distinct high-density core appearing in the central urban area; the main difference is that there are more high-density hotspot areas with larger ranges for holiday visitors. The kernel density of Weibo check-in data shows a generally scattered layout, with more and denser scattered points in the center compared with the edges; there are notable aggregations in certain areas, such as the intersection of mountains, lakes, and rivers. In addition to being related to geographical conditions and the accessibility of transportation, distribution characteristics are also closely related to seasonal changes, historical and cultural customs, and the management methods employed at different scenic spots. Overall, the intensity of endogenous forces in areas with high land development intensity is significantly higher than that in natural landscapes. A high-density core area is formed in the city center, with other local hotspots scattered around (Figure 6).

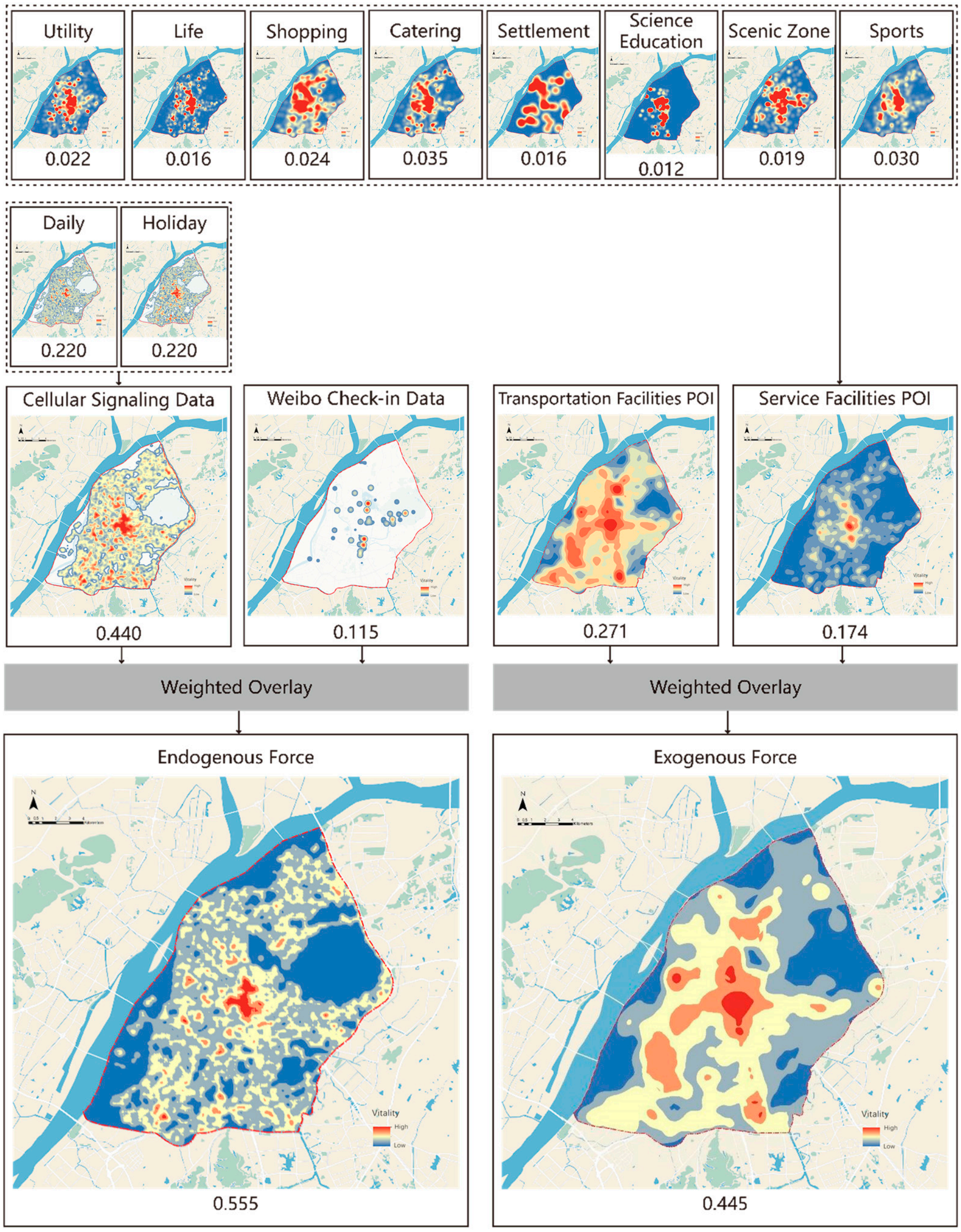

Figure 6. Weight allocation and current evaluation of public vitality factors.

4.2.4. Weighted Superimposition Results

A weighted overlay calculation of exogenous and endogenous factors is performed, and the current public vitality evaluation of each plot is obtained through zonal analysis (Figure 7). The results of the overlay analysis not only confirm the status of the central urban area as a high-density development core, but also reveal the relatively low population density in natural landscape areas. Areas with higher current public vitality are concentrated in group formations, with higher average vitality in the central urban area, extending along the main roads to the north and south; a secondary high-vitality area extends along the main roads in Jianye District southwest of the city center; certain areas near lakes and mountains close to the city center also display relatively high vitality.

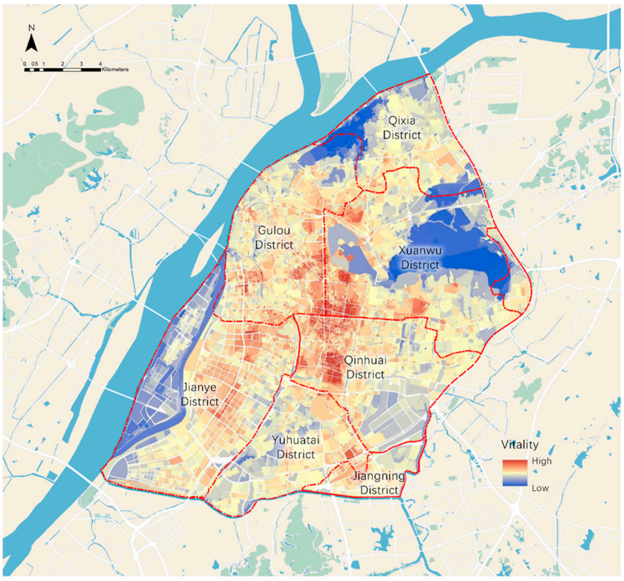

Figure 7. Current evaluation results for public vitality.

4.3. Public Vitality Development Demands

4.3.1. Identification of Public Vitality Source Areas

The identification of public space source areas is shown in Figure 8, with a total of 37 source areas identified, covering a total area of 20.6 km^2. Because "adjacency to public transportation stations" is used as the criterion for screening source areas, those public spaces with large, elongated shapes covering a wide area, such as large parks extending along natural waterways, are more likely to be selected because they are more adjacent to multiple bus stops and subway stations. This characteristic precisely meets the need for public vitality source areas to efficiently channel large numbers of people towards the public space system.

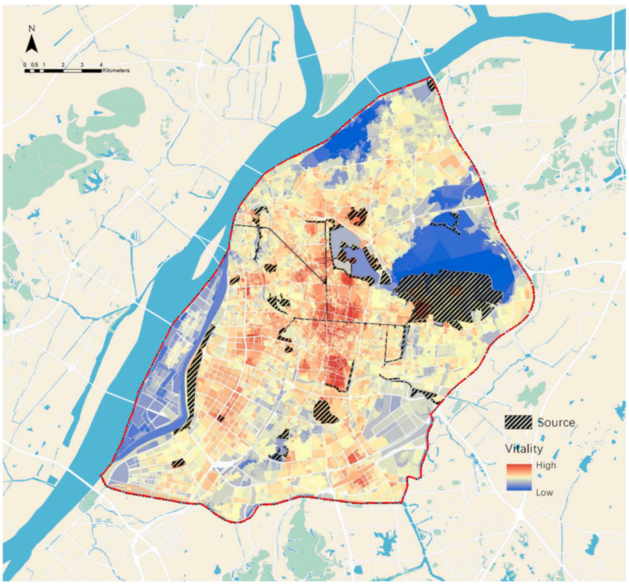

Figure 8. Relationship between public vitality source areas and current public vitality.

The public vitality source areas in the study area show a larger number and wider area in the east–west direction compared with the north–south direction, with a more continuous distribution. The number and area of source areas in the central urban area significantly exceed those in the peripheral districts. Overlaying the distribution of source areas with the current public vitality evaluation results for Nanjing's main urban area reveals that all source areas are distributed at the boundaries, where changes in urban vitality are most pronounced. This phenomenon is closely related to the overall level of development and construction, as well as population density and the completeness of public spaces within the urban area.

4.3.2. Circuit Theory Results

Figure 9 shows the pairwise model results using circuit theory, reflecting the movement of recreational crowds between two areas of public vitality. The current intensity within the main urban area generally remains in the moderate-to-high range, while the current intensity along the road network is generally higher than that across natural elements such as mountains and water bodies. This means that, for recreational crowds, there is a certain intensity between any two adjacent public space source areas within Nanjing's main urban area.

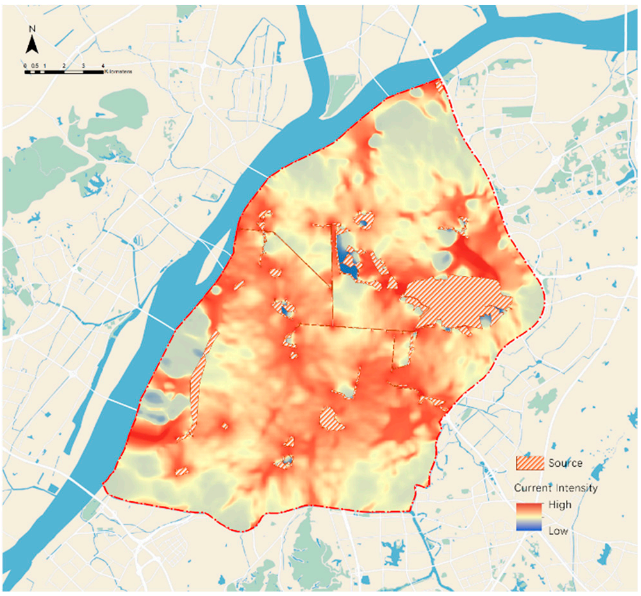

Figure 9. Pairwise results for public vitality.

Figure 10 shows the many-to-one model analysis results using circuit theory, reflecting the flow tendency of recreational crowds across all public vitality source areas within the study area. The current intensity within the main urban area shows significant variations. A clear connecting path is formed from east to west in the central area, which then bends northward, extending from the largest vitality source area in the east to the northwest, finally forming a circular structure that continues to extend southwards and westwards. This means that, for recreational crowds who choose to move continuously through multiple public vitality source areas, their demand shows a clear circular aggregation path with a tendency to extend outwards from the circular route.

Figure 11 shows the Pinchpoint results using circuit theory, highlighting the more important connection nodes between public space source areas. In addition to the circular structure similar to the current intensity in the many-to-one model, a spatial distribution of Pinchpoints also forms a connecting system that radiates both inwards and outwards. This indicates that, for recreational crowds who choose to engage in activities in different public vitality source areas, their preferred public space nodes tend to form a circular connection in the middle, while extending both inwards towards the center, and outwards towards the periphery.

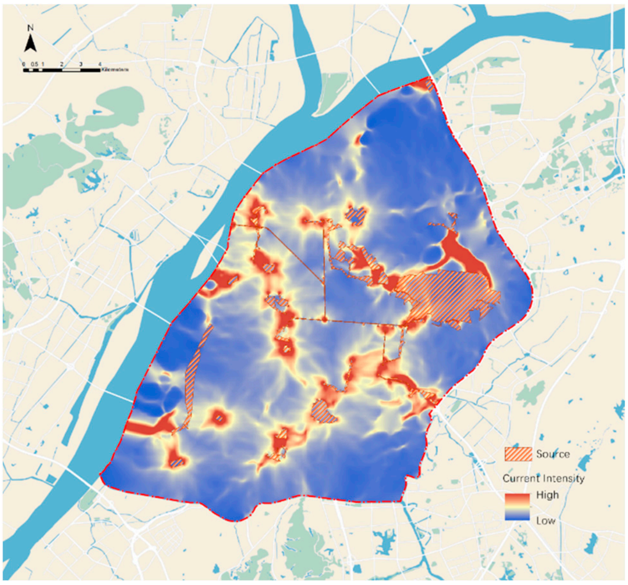

Figure 10. Many-to-one results for public vitality.

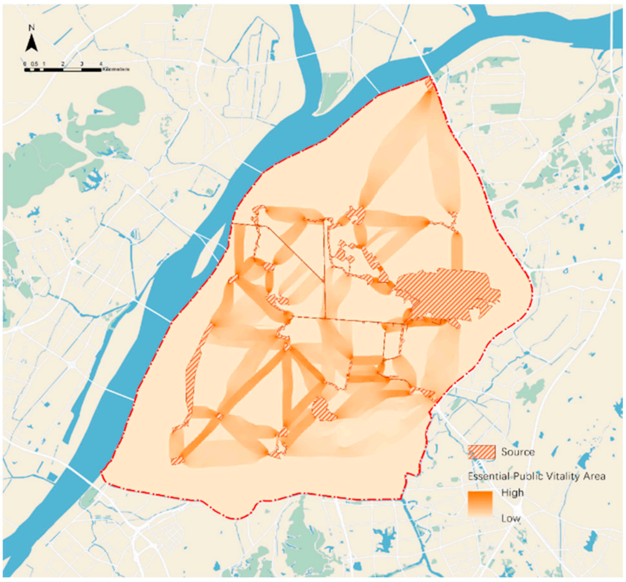

Figure 11. Pinchpoint results for public vitality.

Combining the above three figures, it can be concluded that the public vitality demand in Nanjing will lead to different development paths across different forms of walking conditions. When establishing recreational corridors between any two highly accessible public spaces, recreational crowds show almost no specific preference for the paths within those corridors; however, when the entire public space system is considered, i.e., when recreational crowds need to pass through multiple public spaces, the development of recreational corridors tends to form a circular path along specific elements. This then extends further towards the center and the periphery. When the corridor within the public space network can connect multiple source areas to form a continuous ring, the corridor function of the public space network can be more fully realized.

4.3.3. Demands for Public Vitality

Figure 12 shows the results for silhouette coefficients, indicating that the clustering effect is best when k is 4. The K-means method is used to cluster the standardized circuit theory simulation results on a plot-by-plot basis. The clustered results divide the plots into four different levels of public vitality development demands. This classification reflects the preferences of recreational crowds when moving within and between public spaces. Figure 13 shows the spatial distribution of the results, where the public vitality demand hotspots (cluster = 3) are distributed in clusters; these are mostly located around public vitality source areas, and are mainly concentrated in three areas, namely, the line from northwest to southeast in Gulou District, the center of Jianye District, and the line from west to east in the center of Qinhuai District. The areas with relatively higher demand for public vitality (cluster = 2) are typically distributed between high-demand areas, connecting multiple high-demand hotspots.

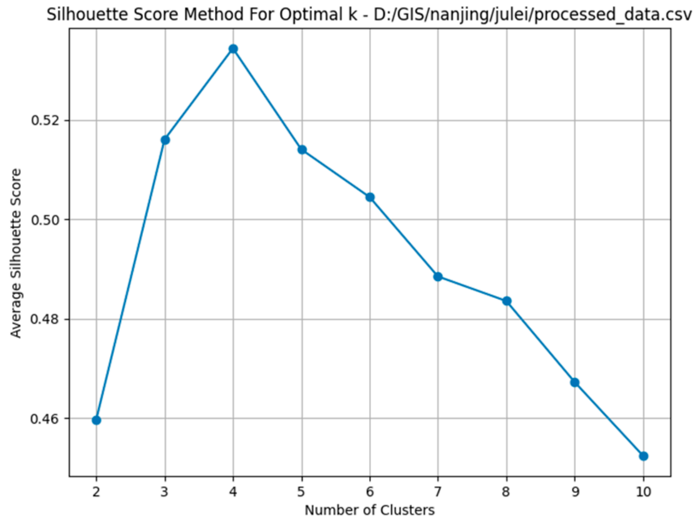

Figure 12. Results of silhouette method.

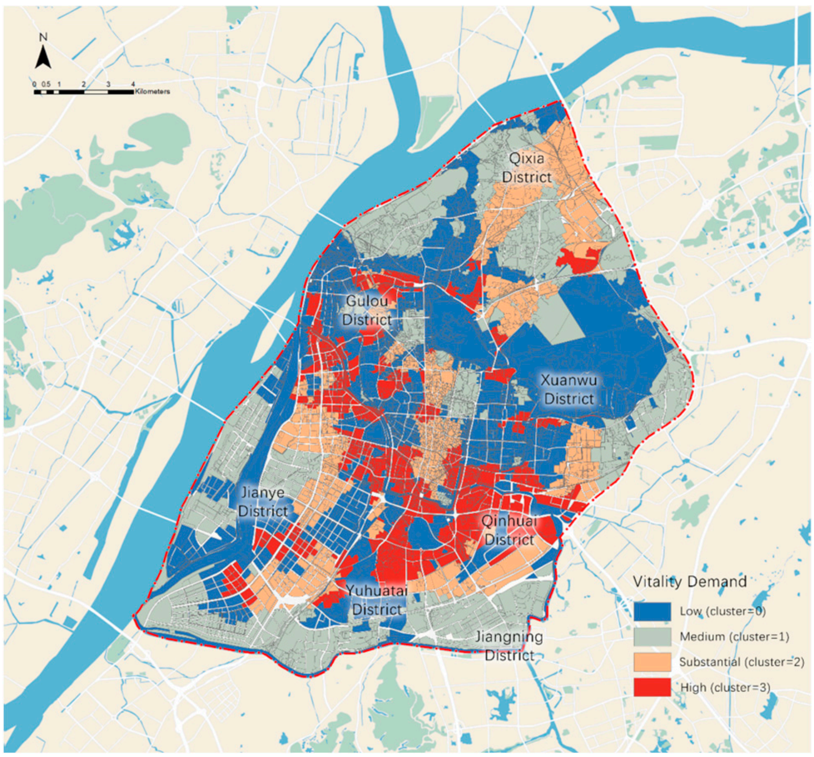

Figure 13. Clustering results for public vitality development demands.

4.4. Public Vitality-Oriented Planning for Nanjing's Main Urban Area

The clustering results for public vitality development demands reveal the existence of a greater recreational demand for transforming open spaces into more public spaces with higher vitality; they also indicate the plots of land corresponding to this demand. Combining land-use data to determine the current usage of plots within the study area, a vitality-oriented enhancement plan for public spaces and a gradual vitality-oriented development plan for open spaces based on the quantitative results of the current public vitality evaluation were formulated. This resulted in a comprehensive public vitality-oriented plan for the city (Figure 14).

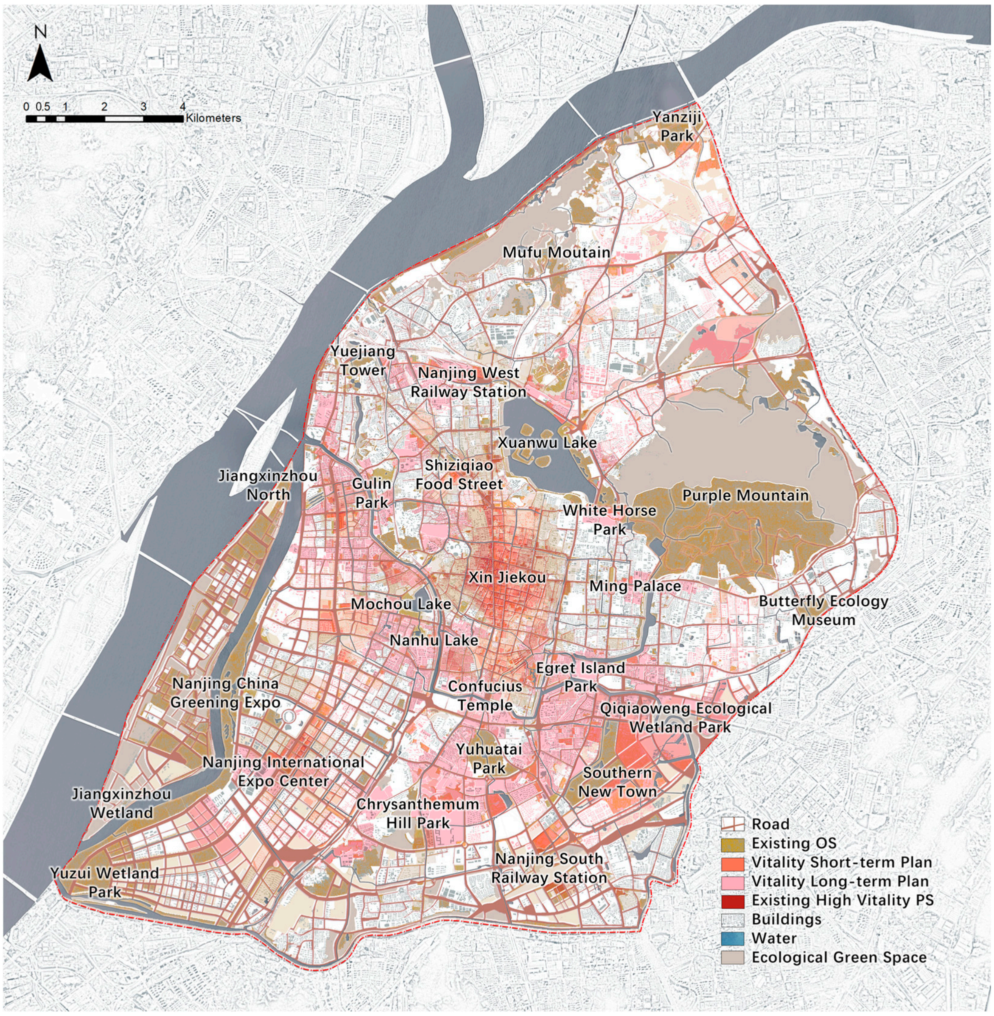

Figure 14. Optimization plan for the public space network.

The public space network system planning for Nanjing's main urban area is suitable for a society marked by high public vitality. It builds upon the existing single-core foundation and emphasizes integration and connectivity, while aligning itself with the natural landscape. This will also link the city's green and gray infrastructure. Starting from the perspective of individual recreational crowd movements within the urban area, this has provided practical reference value for improving public vitality within the city. The main public spaces are distributed along the city walls, stretching from Yuejiang Tower to Gulin Park, Mochou Lake, and Nanhu Lake, following the river southward to Zhonghua Gate, and extending eastward to Qiqiaoweng Ecological Wetland Park. They are further connected in the north to Zijin Mountain and Xuanwu Lake to form a circular structure, which then extends southward to

Yuzui Wetland Park and Juhuashan Park in Jianye District. Other public spaces are found along the north bank of the Yangtze River, such as in Yanziji Park.

5. Discussion

5.1. Path for Optimizing the Public Space Network

The construction of urban public spaces in China has significantly improved in terms of quantity, quality, and public accessibility, with the increasing recognition of the value of public spaces and increased investment from the government. However, due to a lack of systematic planning, today's urban construction policies tend to designate hard-to-develop marginal areas and isolated plots as public spaces. This practice lacks a full assessment and consideration of public needs, as well as a holistic perspective on the layout of public spaces.

Public spaces are centers for the convergence of people and information within a city [3]. The long-standing research approach, focusing on human activities within isolated urban public spaces, has been challenged in recent years by using a method of crowd aggregation created by more diverse, dynamic, and non-permanent physical centers [31]. Through the application of circuit theory, this study analyzes a public space network within a more comprehensive urban environment. The results of this evaluation and optimization can provide effective references for future urban planning and management. The positive social benefits brought to cities by a networked operating model of urban public spaces have also been proposed and discussed [23,32,33]. Based on a virtuous cycle of urban development—public space creation leading to further urban development, which in turn leads back to better public space networks—this study proposes a key path for optimizing public space networks that promote urban development through circuit theory simulation and construction. This included two major steps: evaluating the current status of public vitality to reveal the main issues in the public spaces found within the study area, and evaluating the development demands to derive a set of operational laws for an urban public space network. The optimization strategies for urban public spaces based on this path can be summarized as follows:

1. Update existing public spaces in a targeted manner, improving the supporting transportation infrastructure and service facilities, and increasing the capacity to accommodate more visitors. Upgrade these updated public spaces into "source areas" within the optimization model, and increase the sources of public vitality creation and reproduction within the system.
2. Optimizing the connectivity between existing public spaces, particularly smaller public spaces, and establishing efficient pedestrian and non-motorized traffic networks is crucial. Due to the limited individual scale of such spaces, their functional services are relatively simple. However, the organic combination of multiple smaller public spaces can complement their functions, thereby improving the overall service level. Reduce isolated sites, helping to enhance the overall attractiveness of the public space system and strengthen the social cohesion of the city.
3. Develop new public spaces based on development demands for public vitality, considering a wide variety of factors such as current land-use conditions and location. In highly built environments, considering the limited urban space available, it may be more effective to arrange a network of several smaller public spaces to form a complete and efficient support system for public vitality. This decision can increase the utilization of new public spaces, while having a positive impact on the overall public space system.

5.2. Dynamic Characteristics Brought by a Vitality-Driven Approach

Public vitality emphasizes the dynamic elements generated by humans as social creatures during social interaction. These can act on urban spaces and stimulate the healthy growth of cities and the positive momentum of social evolution [23]. Big data sources, such as satellite data, POI data, and mobile signaling data all have the potential for dynamic updates, as was demonstrated in this study. Under the premise of continuous urban development, this creates opportunities for sustainable public interaction [34] on both sides of the digital divide in urban social spaces [33].

With the continuous development of digital technology, and as urban vitality is generated through communication by individuals via We Media [31], the presence of individuals can also be directly observed at a lower cost. However, this observation may not be definitive, and could be subject to sampling bias and self-selection bias. Social media users are typically concentrated in certain age groups and socioeconomic levels, which may lead to data skew, failing to fully reflect the entire community. Therefore, when utilizing big data sources for analysis, it is important to be aware of these potential biases and adjust for them accordingly to ensure the reliability and validity of the research results. This study, while using circuit theory to simulate the activities of recreational crowds in public spaces, intentionally avoids geographical and temporal biases, adopting a simulation method that more closely reflects the subjects actually generating public vitality. This approach ultimately provides an important basis for the construction of cities with wide public participation, and serves as a decision-making reference. Methods and models used to simulate vitality are constantly upgraded and updated, and are characterized by their comprehensive coverage, iterative process, and dynamic adjustment, thus forming the ability to solve problems in a sustainable manner [35]. The results obtained promote urban resilience by setting a threshold range with a certain degree of redundancy, providing public well-being in a more complex urban socio-ecological environment under the principle of elasticity [34].

5.3. Limitations of the Simulation Model

When simulating the recreational behavior of crowds in public spaces, this study acknowledges certain limitations in the process of establishing the model. Specifically, when the discussion is limited to urban spaces, it becomes difficult to identify the "originating source" of recreational crowds in public spaces, as one might be able to do with ecological flows in green spaces. McRae et al. proposed the omniscape method [36] in 2016, which uses a continuous "circuit surface" instead of a "source area" to output current, and then applies circuit theory for simulation and calculation. The Omniscape method allows for a linear correlation between the total flow and the connectivity of the site, effectively modeling the flow relationships between different landscapes. It is therefore closer to the activity status of recreational crowds in public space systems within cities, significantly reducing computation time while maintaining good resolution [36]. However, when constructing source-weight surfaces, the Omniscape method assigns higher source weights to pixels in a more natural state [36], which makes it more suited to simulating natural environments and less suited to urban settings. This is particularly problematic when urban built environments intersect with natural environment pixels, as the correction for artifacts is weaker. This does not align with the morphological characteristics of public spaces, and contradicts the distribution patterns of urban vitality within these spaces. Therefore, there is still room for further exploration and improvement in the modeling process for simulating crowd activities using circuit theory.

6. Conclusions

Spontaneous recreational activities in public spaces are an important source of public space vitality. However, the existing research in this area often starts with the behavior of crowds within the space, overlooking the movement of crowds between different spatial domains within public spaces. Given the similarity between the random movement of recreational crowds in public spaces and electrons on a two-dimensional circuit surface, this study aims to promote public vitality by applying circuit theory to simulate the movement of individual crowds in urban public spaces. By combining multi-source big data to create a "conductivity surface" that attracts the movement and aggregation of recreational crowds, we simulate and generate the paths that recreational crowds tend to choose between in public spaces, using this as a reference to drive the optimization of public space networks in cities that are in urgent need of development.

This study proposes an urban public space network optimization method that combines existing public vitality evaluations with future development needs. The aim is to further connect and optimize the existing urban public space network, providing a new macro-research approach for improved public space vitality. The method employed is based on public space connectivity, as emphasized in previous research. From concept to application, it presents a practical and feasible implementation method, offering planning and policy guidance for public space optimization and urban vitality management. This approach is therefore suitable for urban social environments seeking high public vitality and sustainability. It maximizes the reduction of geographical and temporal biases, accurately reflecting the vitality and connectivity of public space systems in high-density built areas. Urban public spaces are nested systems, suggesting that the vitality of a certain area often affects or depends on the surrounding spaces. By adopting a holistic perspective and employing both nested and integrated strategies for smart growth and compact urban design, policymakers can ensure the sustainability of urban development and a balanced distribution of vitality. By selecting environmental factors that are suitable for specific local conditions, the optimization method proposed in this study can offer public vitality enhancement solutions for cities with different environmental characteristics. This can in turn provide valuable references and insights for smart cities throughout the world.

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