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A Planning Support Tool for Layout Integral Optimization of Urban Blue–Green Infrastructure

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Abstract: Urban blue infrastructure (UBI) and urban green infrastructure (UGI) can be seen as an integrated system in which services and spatial layouts complement each other. However, given its complexity, it is difficult to integrate and optimize the layout of urban blue and green infrastructure (UBGI) in the built environment. This study develops a planning support tool for the layout integral optimization (PSTLIO) of UBGI. Using Hekou City in China as a case study, service demands and the supply of suitable land for UBGI development are assessed and mapped on geographic information system (GIS). The potential areas for UBGI development are delineated after mapping assessments of service demand and land supply and suitability. Following discussions on the exact means for PSTLIO to support the layout optimization of UBGI, a PSTLIO-based solution is developed to structure the UBGI link network and hub system, define the functions and service patterns of single UBGI components, and provide guidance for determining the scale of UBGI components. The results show that PSTLIO is able to provide a quantifiable base for decision-making in UBGI layout optimization.

Keywords: urban blue infrastructure; urban green Infrastructure; urban planning; suitability; spatial layout; built environment

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1. Introduction

Climate change and the hardening of cities' underlying surfaces have led to a series of environmental issues that present unprecedented challenges to traditional paradigms in urban planning [1]. The concepts and planning theories of urban blue infrastructure (UBI) and urban green infrastructure (UGI) emerged as alternatives to man-made infrastructure. They are currently used extensively in urban planning practice [2].

UBI includes all forms of bodies of water in a city, either natural or artificial, dynamic or static [3], which sustain the basic requirements for running and developing a city. UGI, mainly comprising urban green spaces, such as parks, green buffers, urban forests, wetlands, and green yards, is recognized as an essential support system for natural life and as an interconnected network [4,5]. Although the components of UBI and UGI are totally different, it has become evident that their services and spatial layouts may be correlated and that they can complement each other [6]. Consequently, recent research increasingly considers UBI and UGI as an integrated system and explores their combined environmental and public services [7,8].

Recognized as an effective tool to improve environmental performance at the urban scale, urban blue and green infrastructure (UBGI) plays an increasingly critical role in managing stormwater, improving ecological connections, and mitigating urban heat island effects, among other issues [2,8]. For example, synergy in the layouts of UBI and UGI can take full advantage of the benefits of both green and blue technologies and services [6,9]. UBI and UGI can maintain natural water cycles and increase flood resilience by interacting with urban gray infrastructure [7,10,11]. As a nature-based solution, UBGI could also provide an abundant base for urban ecosystems, in which diverse ecologies and networks could be conserved [12,13]. Moreover, the effects of UBGI in regulating the urban microclimate were also explored in recent studies [14]. It was proven that UBGI could cool urban areas through evapotranspiration, shadowing, adjusting emissivity, and affecting air movement and heat exchange [3,15], indicating UBGI's huge potential in relieving the urban heat island effect (UHIE) [16].

UBGI offers opportunities to significantly improve urban public services [17–20], facilitate social connections, and enhance the quality of public spaces [21,22]. UBGI can boost vitality and increase surrounding land values. It can, thus, be employed as a catalyst for redevelopment [23–25]. Furthermore, the potential benefits of UBGI in terms of aesthetics and spatial definition could also be effectively deployed to preserve and reshape the identity of a site or even a city, especially in the case of key locations such as municipal centers or historic areas [26,27].

Due to UBGI's various benefits, investigations into the integral planning and management of UBGI are currently being carried out all over the world. As a result, a series of interchangeable terms have emerged, including water-sensitive urban design (WSUD) and sustainable urban drainage systems (SUDS) in the UK and Australia, as well as low-impact development (LID) [28] and stormwater best management practices (SBMP) [29] in the United States.

However, in practice, formulating an integral plan for UBGI can be difficult. Integrating blue and green systems, whose different features would probably have been organized in isolation in the past, is challenging. Adapting UBGI to the built environment is itself a task full of complexity and uncertainty [8,30]. For example, in the existing urban context, highly mixed land uses, populations, and facilities would raise diverse demands for UBGI development that would have to be distributed in different patterns with different intensities [19]. However, due to the scarcity of free land in high density areas, the space available for UBGI installation is strictly limited, which calls for a layout model that permits high efficiency and adaptability in UBGI development [31,32]. Although many previous studies have explored layout organization strategies according to a single service demand of UBGI, the issue of how to optimize UBGI layout and respond to multiple service demands simultaneously and efficiently has received less attention, yet this has become increasingly urgent in present day planning practice [33].

The aim of this study is to develop a comprehensive solution for the integral optimization of layout of UBGI in the built environment. Taking the city of Hekou in China as an example, this study has three objectives. The first objective is to build a platform to classify, locate, and quantify the multiple demands for UBGI development. Second, a stacked mapping technology is introduced to assess the availability of suitable land and demonstrate the adaptability and feasibility of UBGI development. Lastly, this study delineates a process for balancing priorities and making decisions in the integral layout optimization of UBGI.

2. Methods

2.1. The Case Study

Hekou City is located in the Yellow River delta in the north of Shandong province, China. Established in 1984, it is an emerging industrial city developed around the headquarters of Shengli oil field, China's second largest oil field. During the period of 1984–2008, the city expanded rapidly, and the extent of developed land increased from 8 km^2 to about 40 km^2 (Figure 1a). However, due to the development pattern set by the oil industry, most of this land was used for oil-related processes and for supporting facilities, which have grown more than five-fold since the city was founded. However, the conservation, planning, and construction of green space and water areas was neglected for decades, resulting in a serious imbalance in land use and a series of environmental and social problems (Figure 1b).

With the ongoing rehabilitation of the city's industrial infrastructure, most of the oil-related structures occupying central locations of the city are intended to be gradually demolished or relocated out of the city. Many of the surrounding industry-supporting facilities and settlements will be renovated. This would offer an important opportunity to rebalance the city's functional and spatial structure. Therefore, one of the main objectives in the plan for the city's renewal is to establish an efficient and synergetic UBGI system to support the future sustainable development of the city.

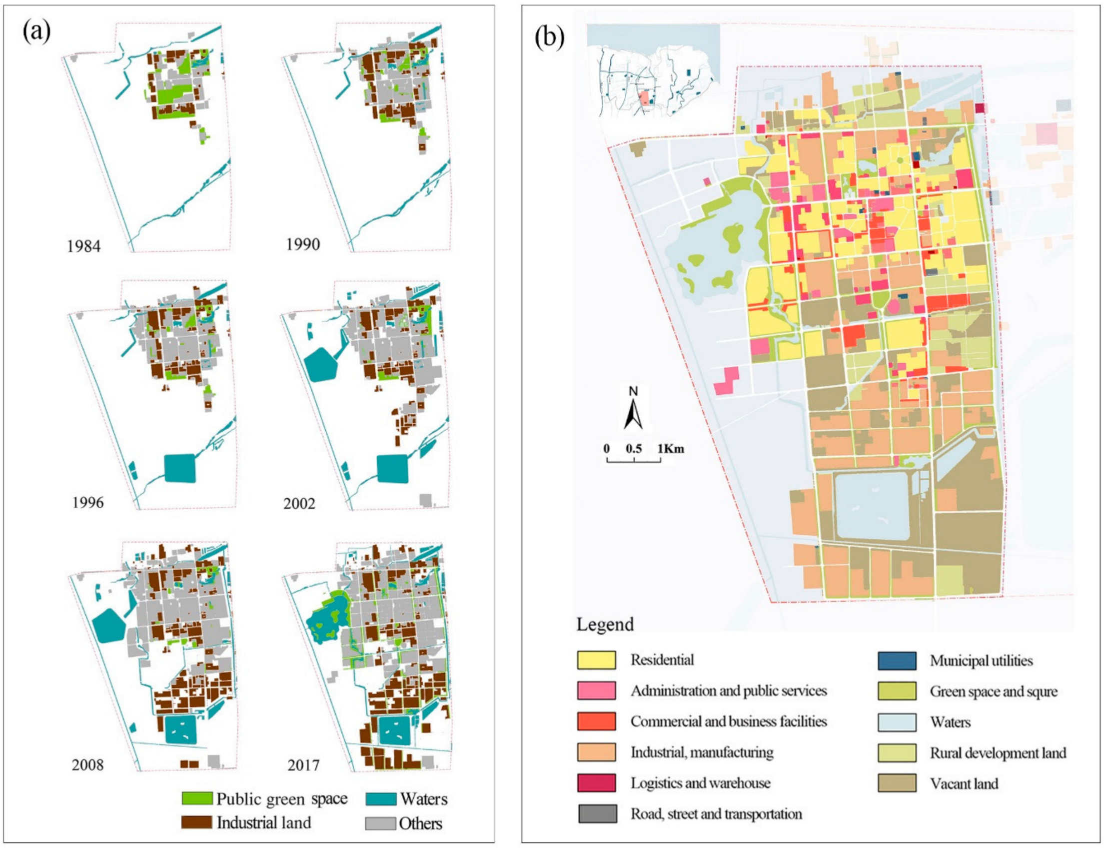

Figure 1. Spatial evolution (**a**) and land use map (2016) (**b**) of Hekou city.

In 2018, we were commissioned by the city government of Hekou to formulate a master plan to guide the development of UBI and UGI up until 2035. In the plan, a specific study on the UBI and UGI layout optimization was initiated. This became the crucial base to support the planning. The city center and peripheral zones, which together comprise a total area of nearly 50 km^2, became the planning and study area. In order to provide guidance for selecting sites, orienting functions, and determining scale in the decision-making process, we developed a planning support tool for the layout integral optimization (PSTLIO) of UBGI. To accurately investigate the multiple demands for UBGI development and land suitability, the process of using the tool was divided into three phases: identification of UBGI service demands (ISD), assessment of land suitability for UBGI development (ALS), and analysis for matching demand with land suitability

2.2. Identification of UBGI Service Demand

The work of ISD includes establishing a set of service demands, assessing demands, and processing and mapping the results. According to existing studies, service demands for UBGI development are diverse and dynamic due to their multifunctionality and regionality [13,19,34]. Generally, all the demand types can be aggregated into two categories: (1) environmental services and (2) public services [19,35]. These two broad categories can then be further broken down into particular demands. The demand types and their composition would foreseeably vary at the scale of the study area according to the development objectives, existing problems, and specific requirements of any given area. In the case of Hekou, 6 types of demand were identified. Among them, stormwater management and drainage (SMD), ecological connectivity promotion (ECP), and heat island effect mitigation (HIEM) belong to the category of environmental services, while recreation opportunity creation (ROC), public vitality enhancement (PVE), and city identity interpretation (CII) are included in the category of public services (Table 1).

Table 1. Rationale for selection of sub-demands and indicators.

Demands	Indicators	Rationale	Data Source
Stormwater management and drainage (SMD)	Runoff intensity of sub-catchment area (RISA)	RISA obtained by the stormwater management model (SWMM) reflects the risk level of waterlogging during the stormy season [36,37].	Land use map (2016) from Hekou Housing and Urban–Rural Development Bureau; drainage system data (2016) and daily rainfall statistics (2015-2017) from Hekou Water Management Bureau
Ecological connectivity promotion (ECP)	Patch area (PA) and Euclidean nearest neighbor (ENN)	PA reflects the level of species diversity that determines the patch value to be protected and connected [38,39]; ENN mainly determines the cost and feasibility connecting a patch [40].	NASA Landsat images of Hekou city (2016)
Heat island effect mitigation (HIEM)	Value above the mean Land surface temperatures (LSTVHM)	The heat island effect of a specific area can be measured by its LST value above the regional mean LST [41].	NASA Landsat 8 remote sensing images of Hekou city (May 10th, 2016)
Recreation opportunity creation (ROC)	Density of urban residents (DUR)	Recreational demand is generated by residents. The intensity of recreational demand will increase with the increase of DUR [22,26,42,43].	Land use map (2016) from Hekou Housing and Urban–Rural Development Bureau; demographic statistics (2016) from Hekou Public Security Bureau
Public vitality enhancement (PVE)	Plot area of public land (PARPL) and floor area ratio of public land (FARPL)	The capacity and the importance of public land is mainly measured by PARPL and FARPL [44].	Land use map (2016) from Hekou Housing and Urban–Rural Development Bureau
City identity interpretation (CII)	Floor area of representative buildings (FARB)	The FARB is assessed to identify the capacity of a plot to shape the identity of the city and the values to be preserved during city renewal [26].	NASA Landsat images of Hekou city (1984-2017); land use map (2016) from Hekou Housing and Urban–Rural Development Bureau

Based on existing research and taking data accessibility into consideration, we selected eight indicators for assessing the six sub-demands (Table 1). Different tools were employed for integrating data and calculating the indicators. Runoff intensity of the sub-catchment area (RISA) was obtained from the stormwater management model (SWMM) [9,45,46], which can integrate urban rainfall, topography, and the existing layouts and capacities of drainage facilities. This tool can simulate the locations, routes, and intensities of urban surface runoff and predict the areas at risk of flooding and waterlogging [46,47]. Patch area (PA) and Euclidean nearest neighbor (ENN) were calculated through the landscape spatial analysis models on the software of FRAGSTATS (Version 4.2, 2015) [38,40,48]. Land surface temperatures (LST) were derived from the thermal infrared band analysis from remote sensing images. By analyzing the variability in LST with the spatial analysis tools offered by the software of ArcGIS (Version 10.5, 2016), the areas with LST higher than the regional mean LST were outlined, and values above the mean LST (VAMLST) were quantified in each area [16,41,49]. The density of urban residents (DUR) [50,51], the plot area of public land (PARPL), the floor area ratio of public land (FARPL) [52], and the floor area of representative buildings (FARB) [26] were all measured on the land use map with the ArcGIS spatial analysis tool.

A grading system and map stacking technology allowed us to simplify, integrate, and demonstrate the assessment results of both ISD and ALS. This model was first developed by I. L. McHarg for assessing suitability for landscape planning [53]. With the capacity to integrate multiple factors from different fields, this model is continuously expanding to assess supply and demand of UBGI [43,54], development suitability [55,56], and ecological sensitivity [57]. Following this model's basic principles and existing research [35,43,57,58], the distribution of the assessment values was taken, which informed the range of each variable in this study's grading system (Table 2). After grading, GIS was used to map the locations and intensities of each demand in the city and to stack the maps together for analysis.

Table 2. Urban blue and green infrastructure (UBGI) service demand grading system.

Variables	Service Demand Class (Scoring)	Class Description
SMD	very high (5)	RISA > 6 cu.ft/s
	high (4)	5 < RISA ≤ 6 cu.ft/s
	medium (3)	3 < RISA ≤ 5 cu.ft/s
	low (2)	1 < RISA ≤ 3 cu.ft/s
	very low (1)	others
ECP	very high (5)	PA > 20 ha, ENN < 60 m
	high (4)	PA > 10 ha, ENN < 90 m
	medium (3)	PA > 5 ha, ENN < 120 m
	low (2)	PA > 1 ha, ENN < 250 m
	very low (1)	others
HIEM	very high (5)	LSTVHM > 2.5 °C
	high (4)	1.5 ≤ LSTVHM ≤ 2.5 °C
	medium (3)	0.5 ≤ LSTVHM ≤ 1.5 °C
	low (2)	−0.5 ≤ LSTVHM ≤ 0.5 °C
	very low (1)	Others
ROC	very high (5)	DUR > 300 capita/ha
	high (4)	200 < DUR ≤ 300 capita/ha
	medium (3)	100 < DUR ≤ 200 capita/ha
	low (2)	50 < DUR ≤ 100 capita/ha
	very low (1)	others
PVE	very high (5)	FARPL > 4, PARPL > 20 ha
	high (4)	FARPL > 3, PARPL > 15 ha
	medium (3)	FARPL > 2, PARPL > 10 ha
	low (2)	FARPL > 1, PARPL > 5 ha
	very low (1)	Others
CII	very high (5)	FARB > 5000 m^2
	high (4)	2000 < FARB ≤ 5000 m^2
	medium (3)	1000 < FARB ≤ 2000 m^2
	low (2)	200 < FARB ≤ 1000 m^2
	very low (1)	Others

2.3. Assessment of Land Suitability for UBGI Development

In keeping with the requirements for the UBGI development [8,17,59], six variables are selected to assess land suitability, including policy-related [56,60] and physical factors [61]. The variables were classified into two categories: (1) potential land acquisition (PLA), which describes the potential for acquiring land for UBGI development based on planning policy and the land's existing condition [32,42]; and (2) feasibility in installation (FII), which outlines suitability at the physical, ecological, and construction levels [62,63]. Potential for land use conversion (PLUC) is used to demonstrate the potential for converting the entirety of an existing land parcel [35]. Potential for space integration (PSI) [37,64] and potential for facilities replacement (PFR) [65] are used to describe the potential for partial land use conversion of an existing parcel. In the category of FII, elevation, slope, and the intensity of natural runoff (IOR) are finally selected, following a review of the variables used in existing research [35,58,63] and a summary of the shared physical requirements for developing and running UBI and UGI [6,8,9] (Table 3).

Table 3. Rationale of selection of variables and indicators.

Variables	Indicators	Rationale	Data Source
Potential for land use conversion (PLUC)	Existing land use	Inconsistencies between the existing land use of a parcel and the city renewal strategy will determine the potential of the land-use conversion of the parcel into UBGI [35].	Land use map (2016) from the Hekou Housing and Urban–Rural Development Bureau
Potential for space integration (PSI)	Rate of open space (ROS)	The ROS reflects the potential of the existing space in a parcel for UBGI integral installation [37,64].	Land use map (2016) from the Hekou Housing and Urban–Rural Development Bureau
Potential for facilities replacement (PFR)	Rate of facilities (or buildings) in poor quality (or efficiency) (RFPQ)	The RFPQ reflects the potential of the existing facilities or buildings in a parcel to be replaced by UBGI [65].	Building age, usage, and quality assessment (2018) from the Hekou Housing and Urban–Rural Development Bureau and research team
Elevation	Elevation (EL)	EL is assessed to identify the site's physical condition and the feasibility of UBGI installation [66].	Elevation and underlying surface data (2017) from the Hekou Land and Resources Bureau
Slope	Slope (SL)	Aligned with EL, is also a key factor in determining the site's physical condition and the feasibility of UBGI installation [66].	Elevation and underlying surface data (2017) from the Hekou Land and Resources Bureau
Intensity of natural runoff (IOR)	Number of catchment units (NCU)	NCU is assessed to identify the intensity of the natural runoff according to the site's physical conditions. Locations with high NCU are prioritized for UBGI installation [1,67].	Elevation and underlying surface data (2017) from the Hekou Land and Resources Bureau

According to the attributes of each variable and data accessibility, six indicators were used to measure the six variables. The PLA indicators were calculated by passing data pertaining to land use and existing building conditions through the spatial analysis tool on GIS. Data pertaining to elevation and underlying surfaces were used to establish a digital elevation model (DEM) in GIS and generate the values of the indicators for FII [35,58,62,64]. As in the case of the assessments of ISD, the results of the ALS assessment were processed through a grading system and mapped individually and integrally on GIS (Table 4).

Table 4. Land suitability grading system for UBGI development.

Variables	Land-Suitability Ratings (Scoring)	Description
PLUC	very high (5)	Wasteland and vacant land
	high (4)	Industrial use to be relocated
	medium (3)	Office and commercial use affiliated with oil field
	low (2)	Residential land affiliated with oil field
	very low (1)	Others
PSI	very high (5)	ROS > 90%
	high (4)	70 < ROS ≤ 90%
	medium (3)	50 < ROS ≤ 70%
	low (2)	30 < ROS ≤ 50%
	very low (1)	Others

Table 4. *Cont.*

Variables	Land-Suitability Ratings (Scoring)	Description
PFR	very high (5)	RFPQ > 50%
	high (4)	40 < RFPQ ≤ 50%
	medium (3)	30 < RFPQ ≤ 40%
	low (2)	20 < RFPQ ≤ 30%
	very low (1)	Others
Elevation	very high (5)	0 < EL ≤ 4 m
	high (4)	4 < EL ≤ 5 m
	medium (3)	5<EL ≤ 7 m
	low (2)	7 < EL ≤ 10 m or −3 < EL ≤ 0 m
	very low (1)	others
Slope	very high (5)	SL < 1°
	high (4)	1 < SL ≤ 3°
	medium (3)	3 < SL ≤ 7°
	low (2)	7 < SL ≤ 11°
	very low (1)	others
IOR	very high (5)	NCU > 150000
	medium (3)	80000 < NCU ≤ 150000
	very low (1)	NCU < 80000

2.4. Demand-Suitability Matching Analysis

The relationship between service demand and the suitability of land for UBGI development can be thought of as the relationship between the demand and supply for the future allocation of land resources towards UBGI [60]. In order to determine areas where each service demand and supply were best matched, the results of ISD and ALS were stacked and integrated using the spatial analysis tool on GIS. The areas with high scores both in ISD and ALS showed the greatest potential for UBGI development to meet a specific demand. Six integration maps were finally generated. They provide a quantitative and visualized tool to support the decision-making process of UBGI layout optimization (Figure 2).

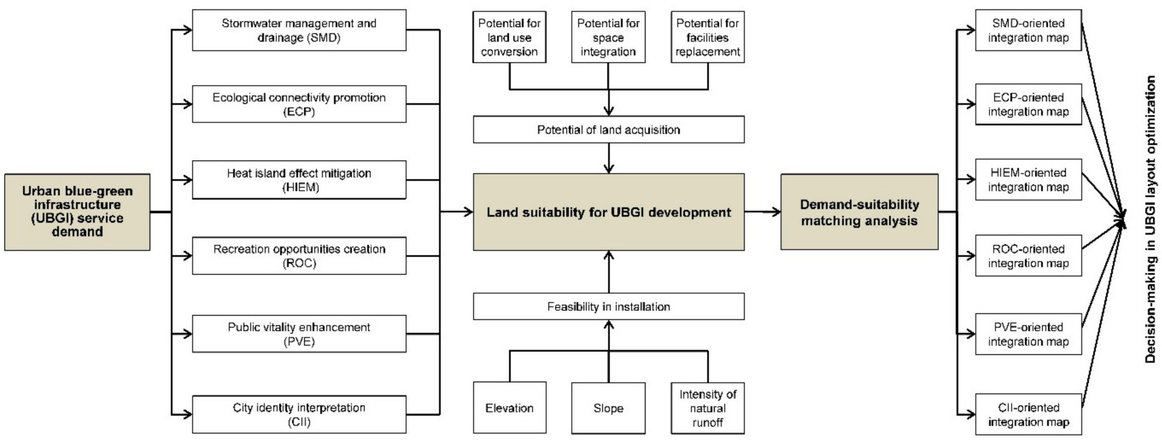

Figure 2. Conceptual framework and application roadmap of planning support tool for the layout integral optimization (PSTLIO).

3. Results

3.1. UBGI Service Demands Mapping

Figure 3 displayed the process of the SMD demand assessment for Hekou City. Simulations generated calculations for RISA (Figure 3c) and provided the basis for assessing the risk of waterlogging and assigning grades to SMD demands (Figure 4a). These simulations were done after dividing the watershed area (Figure 3a), constructing a rainwater drainage system, generalizing the pipe network (Figure 3b), and implementing regional rainfall data. The results showed that the areas with very high (scoring 5) and high (scoring 4) demands for SMD are concentrated in the densely populated northern section of the city.

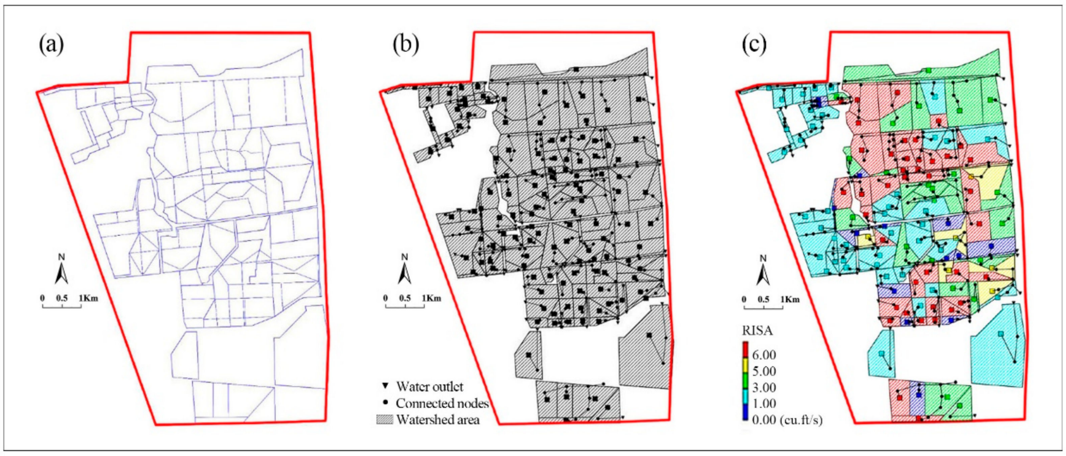

Figure 3. SMD demand assessment process: (**a**) division of watershed area; (**b**) generalization of the pipe network; (**c**) intensity of runoff in the sub-catchment.

The assessment results of ECP demand (Table 5, Figure 4b) show that 56.94% of the city's patches of land have strong demands (scoring 5 and 4) for connectivity. However, most of these landscapes with high ECP demand were distributed at peripheral areas of the city, with a serious scarcity of patches in the densely populated areas at the northern edge of the city. Moreover, the patches remaining in the inner city were small and poorly connected, demonstrating the issue of uneven distribution of ecological resources and the spatial separation between residences and green spaces or bodies of water.

According to the results of the HIEM demand assessment (Table 5, Figure 4c), the areas with the most serious UHI—those in which the temperature was 2.5 °C higher than the average land surface temperature—were mainly distributed in the city center and in the residential area to the west. Nevertheless, the overall ratio was relatively low (1.58%). In most of the urban areas (81.69%), the difference from the average land surface temperature was between −0.5 °C and +1.5 °C. The large lake in the west and the reservoir in the south significantly mitigated UHIE, and the surface temperatures of the areas surrounding these two sites were at least 2.5 °C lower than the average land surface temperature.

Intense ROC demands (Table 5, Figure 4d) were concentrated in the densely populated areas to the north and distributed in a circular pattern around the old city. Compared to the other demands in the category of UBGI public service, areas with high PVE demands (Table 5, Figure 4e) were much smaller and more scattered in the city center and southeast of the lake.

The results of CII demand assessment (Table 5, Figure 4f) demonstrated that the areas that contributed the most to shaping the identity of the city were located along Yellow River Road, the city's main east–west axis, and Haihe Road, the main north–south axis. Additionally, a ring-shaped area around the old city also gained a high score in terms of CII demands. This once constituted the border of the old city and includes the sites of old oil factories, office buildings, and facilities.

Table 5. Assessment results of the UBGI service demand.

Variables	Distribution of Scores in the City Area (%)				
	Very High (5)	**High (4)**	**Medium (3)**	**Low (2)**	**Very Low (1)**
SMD	17.56	3.61	15.61	19.97	43.24
ECP	47.63	9.31	6.91	11.65	24.50
HIEM	1.58	5.86	47.52	34.17	10.87
ROC	10.52	9.82	9.98	18.69	50.99
PVE	0.50	1.09	1.12	1.63	95.66
CII	3.35	2.36	7.58	3.82	82.88

Figure 4. Mapping of the UBGI Service demands: (**a**) SMD demand mapping; (**b**) ECP demand mapping; (**c**) HIEM demand mapping; (**d**) ROC demand mapping; (**e**) PVE demand mapping; (**f**) CII demand mapping.

3.2. Land Suitability Mapping for UBGI Development

The indicators of PLA demonstrated that most areas with high scores in PLUC (Figure 5a) and PFR (Figure 5c) were concentrated in the old city to the north. The areas with high scores in PSI were randomly scattered in the center and southeast of the city (Figure 5b).

The integrated results of PLA analysis were obtained by stacking the areas with high scores (4 and 5) in PLUC, PFR, and PSI assessment together (Figure 5d). The results proved that the areas with high PLA for UBGI development were concentrated in the central areas to the south and in the periphery of the old city to the north, the location of the industrial facilities and residential settlements that would be either renovated or removed as part of plans for rehabilitation.

The results of the FII assessments (Table 6) show that Hekou is generally flat, with an elevation varying between 4 m and 7 m (Figure 5e), and dropping slowly from the southwest to northeast of the city (Figure 5f). Surface runoff was evenly distributed in the city (Figure 5g). The integrated results of FII assessments showed that the northern part of the city was more suitable for UBGI installation than the southern part, which coincides with the distribution of most UBGI service demands (Figure 5h).

Table 6. Assessment results of the land suitability for UBGI development.

Variables	Distribution of Scores in the City Area (%)				
	Very High (5)	High (4)	Medium (3)	Low (2)	Very Low (1)
PLUC	44.56	3.24	2.87	14.47	34.85
PSI	17.51	12.79	12.53	5.19	51.98
PFR	6.96	4.79	2.54	13.90	71.81
Elevation	4.86	37.42	41.75	14.75	1.22
Slope	68.36	21.63	7.63	1.85	0.53
IOR	4.99	–	77.29	–	17.72

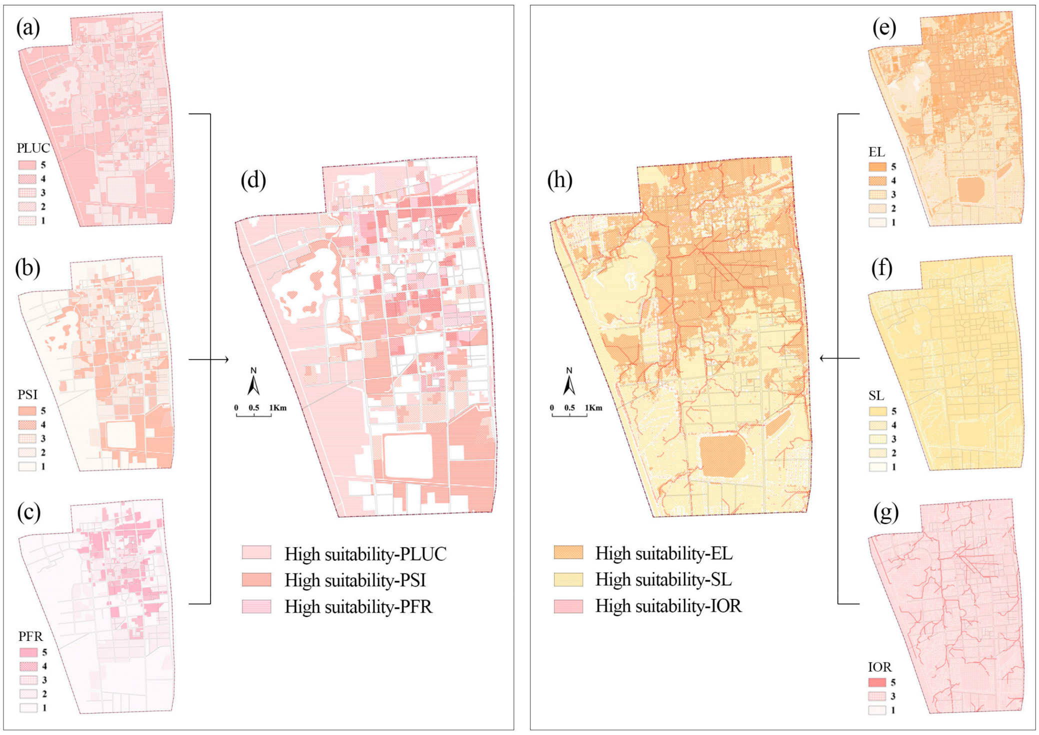

Figure 5. Mapping of the land suitability for UBGI development: (**a**) PLUC map; (**b**) PSI map; (**c**) PFR map; (**d**) integration map of PLA; (**e**) elevation map; (**f**) slope map; (**g**) IOR map; (**h**) integration map of FII.

3.3. Potential Areas Generated for UBGI Development

Potential areas for UBGI development were generated after mapping the assessment result of each service demand together with results related to land suitability. Six maps were generated to show areas that could be developed as UBGI based on specific service demands (Figure 6).

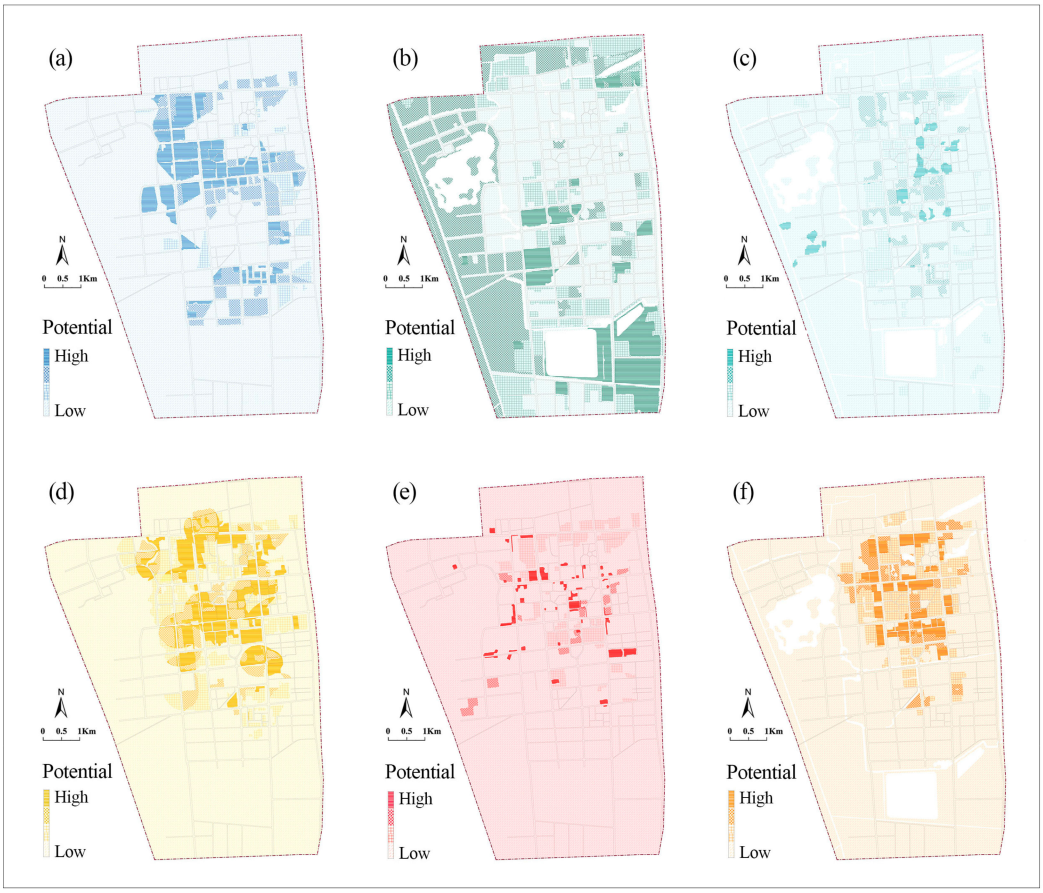

Figure 6. Mapping of the potential and priority areas for UBGI development: (**a**) SMD-oriented demand-suitability integration map; (**b**) ECP-oriented demand-suitability integration map; (**c**) HIEM-oriented demand-suitability integration map; (**d**) ROC-oriented demand-suitability integration map; (**e**) PVE-oriented demand-suitability integration map; (**f**) CII-oriented demand-suitability integration map.

4. Support to UBGI Layout Optimization

The functional and spatial components of UBGI can be classified as "hubs" and "links" [4]. Hubs are essential nodes in UBGI systems and include various functional anchors with different scales, such as urban parks, community parks, wetlands, lakes, reservoirs, and ponds [4]. Links are the keys to connecting and integrating the elements within the system [8]. These connections are important guarantees for the basic performance of the ecological, social, and cultural mechanisms within the system [68]. Correspondingly, the core work in the optimization of the layout of UBGI includes improving the link network and improving the hub system.

4.1. Support for the Layout Optimization of the UBGI Link Network

4.1.1. Structuring in Response to Multiple Service Demands

Alternate proposals for link networks were devised in accordance with the distribution patterns shown on the integrated map. These proposals were guided by the principle of connecting potential and existing bodies of water and green space, while still following the city fabric and morphology (Figure 7). By stacking six demand-oriented link structure proposals together, overlapping or adjacent links could be combined. These would yield sites for development that could respond to multiple service demands.

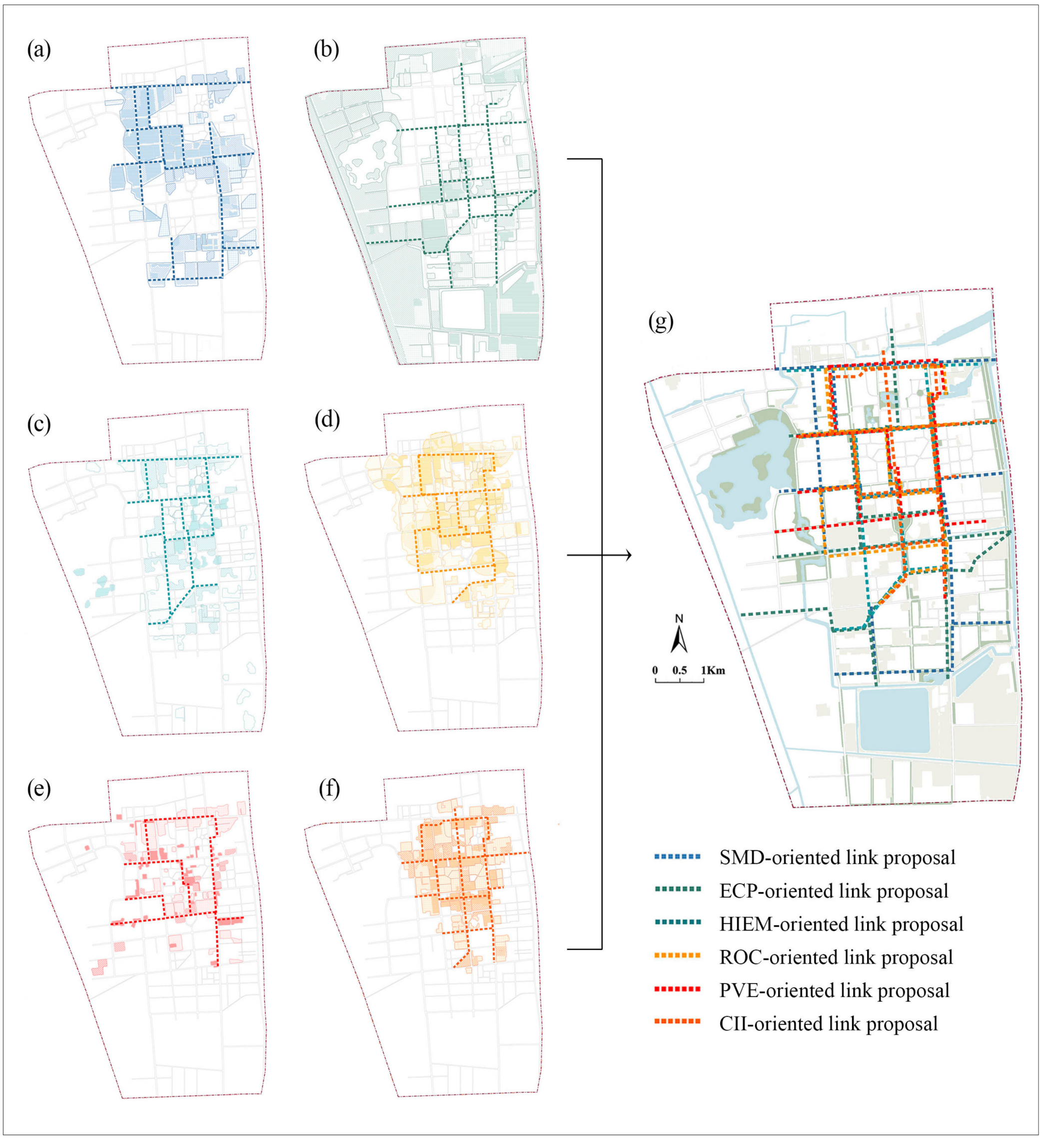

Figure 7. Link structure alternate proposals and integration analysis: (**a**) SMD-oriented proposal; (**b**) ECP-oriented proposal; (**c**) HIEM-oriented proposal; (**d**) ROC-oriented proposal; (**e**) PVE-oriented proposal; (**f**) CII-oriented proposal; (**g**) stacked mapping of six alternate proposals.

As an example, in cases where the layouts for alternate proposals did not line up, it was difficult to keep all the links from every potential proposal due to limitations in usable land. In the deliberation process for Hekou City, priority in structuring the link network was given to the most significant or urgent service demand. Other services could later be integrated within the primary network. In this study, the proportion of areas with the highest intensity in each service demand determined which service demands were of primary importance.

4.1.2. Integration into the Existing and Regional System

In addition to service demand and suitability, existing bodies of water and green spaces were given priority. They provided a basic framework for structuring the link network. For example, the outer ring of canals that connects the lake and the reservoir around the city was an important channel for water drainage at the urban scale. Moreover, the unconnected bodies of water and green space scattered within the inner city were also considered a valuable resource to be integrated within the link network (Figure 8a).

In regional scale, three regional rivers in the east, west, and south of the city play important roles in water replenishment (Figure 8b), flood discharge, and drainage (Figure 8c). The large areas of farmland, woodland, and wetland in the east and north of the city are high-quality ecological resources (Figure 8d) that could contribute considerable ecological and hydrological benefits to the city once they are properly integrated into the network.

Figure 8. Existing and regional green and blue systems of Hekou city: (**a**) existing water and green spaces; (**b**) water replenishment directions; (**c**) flood discharge directions; (**d**) distribution of regional blue and green resources.

4.1.3. Scale and Function

A comprehensive proposal with 22 links was formulated, combining multiple service demands, existing components, and regional systems (Figure 9a). A three-class classification system was adopted to regulate the relative importance of the link service and to determine scale. Based on the clustering feature of the scores of the 22 links, 3 were proposed as first-class links requiring the largest scale to meet the most intense and comprehensive service demands at a regional or city level. Additionally, 6 links and 13 links were classified as second-class and third-class links, respectively (Figure 9b).

Meanwhile, the composition of the overall demand scores of each link provides an effective reference for defining functions and service patterns, and for guiding facility allocation and future design. Results of comparisons between environmental service and public service demands in the links show that all first- and second-class links were environmental services (ESD), and most third-class links were public service dominated (PSD). This indicates that links at a higher class and larger scale should contribute more to the improvement of the environment at the regional or urban scales, while the smaller links would play key roles in enhancing public services at the district or community levels (Table 7).

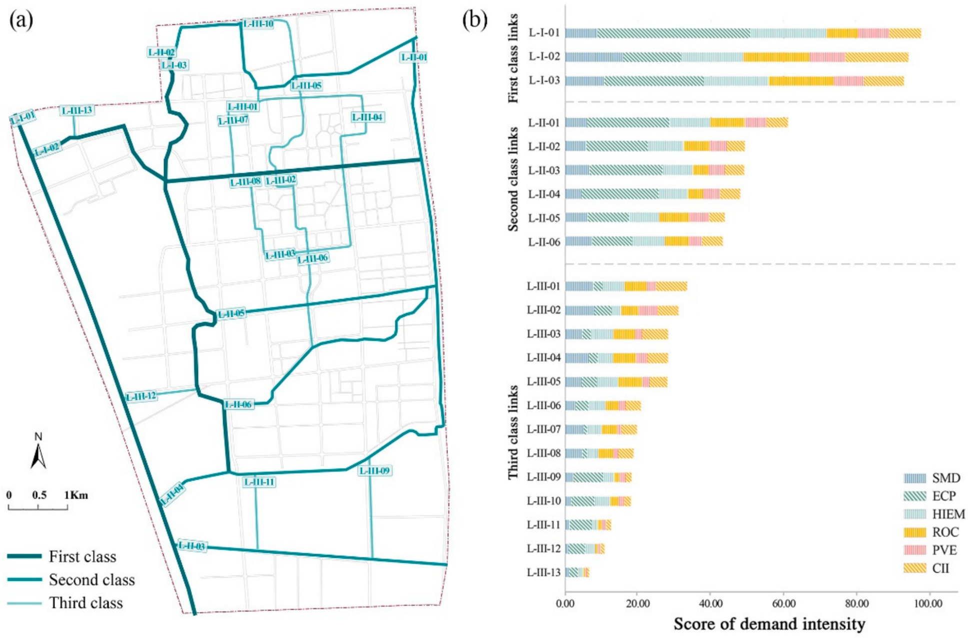

Figure 9. UBGI link network layout proposal and class division: (**a**) UBGI link network structure and layout proposal; (**b**) classification of links according to the overall score of demand intensity.

Table 7. Scale regulation and service and function definition of each class of links.

Link Class	Serving Level	Width (m)	Distribution of the Service Pattern		Function and Service Definition
			ESD	PSD	
1	Region/city level	≥ 120	3	–	Ecological corridor connecting urban and regional ecosystem; channel of flood discharge and water replenishment at city level
2	City/district level	≥ 60	6	–	Ecological corridor connecting key patches within the city; channel of flood discharge and water replenishment at district level; main recreational route and scenery axis
3	District/community level	≥ 30	5	8	Branch ecological corridor; channel of flood discharge and water replenishment at community level; community recreational route and branch scenery axis

4.2. Support for the Layout Optimization of UBGI Hub System

4.2.1. Positioning

As in other UBGI systems, hubs would be attached to the link network. In Hekou, after structuring the link network, the values for demand intensity and land suitability could be placed along the link, forming quantitative and visualized segments to help determine hub positions. The ideal position for hub installation is the segment of a link with both high scores in demand intensity and land suitability, such that service demands are concentrated at the place most suitable for hub development.

However, for example, in cases where the segments with the highest scores of demand intensity and land suitability were not aligned, it became a matter of striking a delicate balance between the two. In Hekou, priority was given to segments with the highest values in land suitability and relatively high values in demand density to ensure that hub installation was feasible. Additionally, in cases where the segments with high environmental service demand and public service demand occurred in different locations with similarly suitable land, the segment with higher service demand was prioritized (Figure 10).

As a result of the analysis, 29 UBGI hubs were finally positioned within the network (Figure 11a). Almost 70% of the hubs were concentrated at the north of the city, which was consistent with the distribution of the demand intensity and land suitability. Among the 9 hubs to the south, 4 were existing reservoirs and lakes. Only 5 were newly installed and were mainly positioned in response to the ECP and SMD demand.

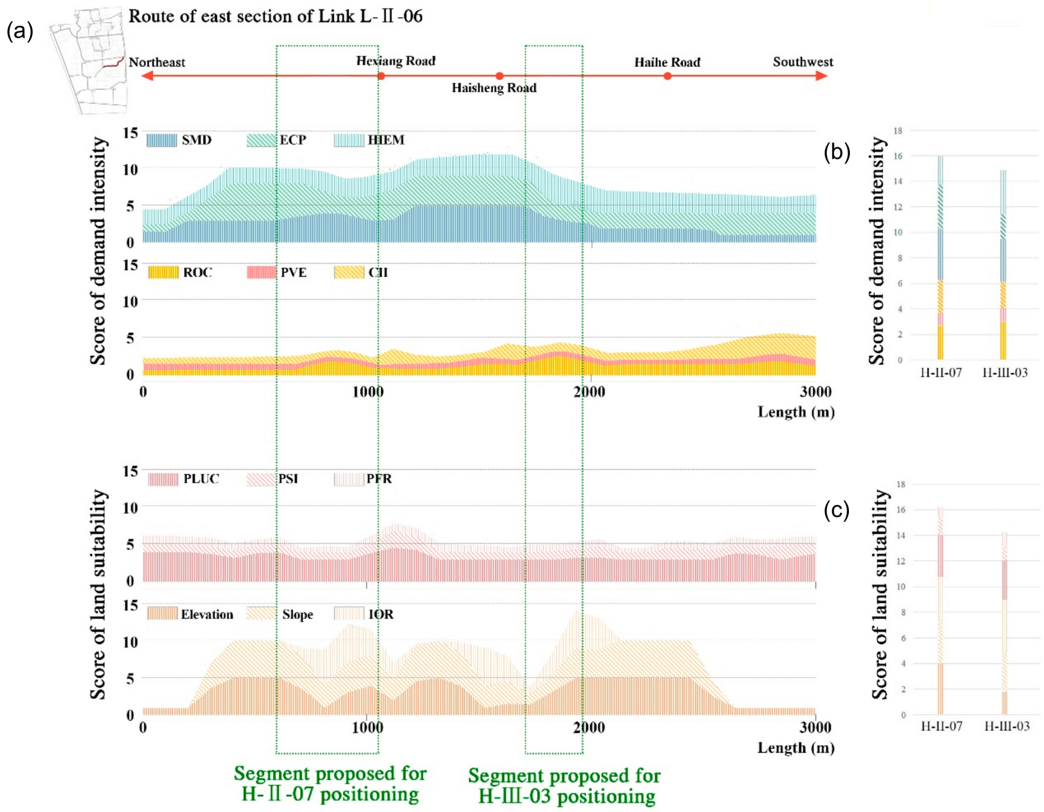

Figure 10. An example of hub positioning (H-II-07 and H-III-03 at the east section of Link L-II-06): (**a**) identification of segment for hub positioning according to the variation of the scores of demand intensity and land suitability along the link; (**b**) average score of demand intensity of the segment proposed for hub positioning; (**c**) average score of land suitability of the segment proposed for hub positioning.

4.2.2. Scale and Function

Using a similar classification system and method, the class of each hub was defined according to the overall score of the proposed segment in the link, and the function and service pattern was determined by the composition of the demand intensities.

The 2 hubs with the highest overall demand intensity scores were classified as first-class hubs. These two hubs are meant to serve as the city's principal ecological area, recreational center, and center for rainwater-collection and regulation. Meanwhile, the 9 and 18 hubs classified as second- and third-class links are meant to function primarily at the level of the district and community (Figure 11b).

ESD hubs were the majority in all three classes, accounting for nearly three-quarters of the total number. As with the links, PSD hubs were absent in the first class and were mainly found in the third class (Table 8).

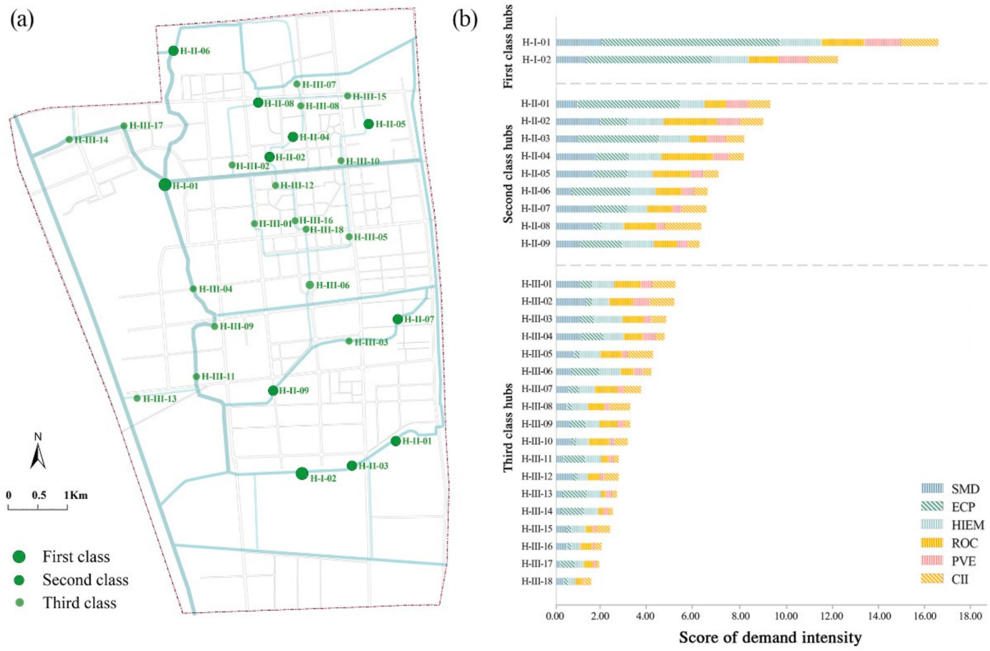

Figure 11. UBGI hub system layout proposal and classification: (**a**) UBGI hub system layout proposal; (**b**) classification of hubs according to the overall score of demand intensity.

Table 8. Scale regulation and service and function definition of each class of hubs.

Hub Class	Serving Level	Area (hm2)	Distribution of the Service Pattern		Function and Service Definition
			ESD	PSD	
1	City level	≥ 40	2	–	Main ecological patch; rainwater collection and regulation center at city level; city recreational center
2	District level	≥ 10	7	2	Secondary ecological patch; rainwater collection and regulation center at district level; district recreational center
3	Community level	≥ 1	12	6	Small ecological patch; rainwater collection and regulation node at community level; community recreational node

4.3. Blue or Green?

Traditionally, plans for blue and green systems were formulated independently by different government departments, with the services and layouts of water and green space examined in isolation [11,30]. However, there are significant compound effects generated from combining water and green spaces [9]. For example, bodies of water and waterfront green spaces could cooperate effectively in controlling floods, serving residences, enhancing vitality, and mitigating heat island effects. This offers a strong basis for installing integrated UBI and UGI.

However, because requirements for site conditions and connectivity are much more stringent for UBI than for UGI, not all places suitable for UGI development are also suitable for UBI. In the case of Hekou, two methods were employed for distributing UBI or UGI. The first method calls for the integration of UBI and UGI. In such cases, the layout and scale of UBI was set first, and the UGI was subsequently installed along the UBI, in accordance with UBI layout and with the conditions of surrounding lands. The second method calls for UBI and UGI to complement each other. In this method, the flexibility of UGI was prioritized. In areas with strong demand for UBGI services but low feasibility for UBI installation, UGI was proposed as an independent solution that could complement

UBI. For example, when determining UBGI layout in areas with high SMD demand density where canals are feasible, UBI and UGI can be deployed as an integrated system by setting buffer greenbelts along each canal. However, in specific areas where building UBI for drainage is not feasible, UGI, such as bioswales, could be installed as temporary drainage channels during the rainy season.

In the final proposal of the UBGI layout planning of Hekou city confirmed by the commissioner (Figure 12), we can see the positions, sizes, and service patterns of the UBGI components were determined based on the results gained from PSTLIO. However, PSTLIO could not directly generate the most effective distribution of blue or green spaces within a component. It is difficult to achieve this objective solely with the grading scores showing demand intensity and land suitability. In this study, additional work, such as computations for flood regulation, would be necessary in order to determine the scale and proportion of UBI and UGI for each component, and to finally formulate the UBGI layout proposal.

Figure 12. Final proposal of the UBGI layout planning of Hekou city.

5. Discussion

Given the multitude of demands and scarcity of land, tradeoffs between different benefits will always be a part of the process of UBGI layout formulation. In order to make the process more effective, these tradeoffs need to be understood and negotiated to ensure that the public resources used for UBGI development are allocated to the areas that need them most. The main purpose of establishing PSTLIO is to offer an open and flexible platform to support the decision-making process while planning UBGI. This process is influenced simultaneously by different policy-related, societal, ecological, and cultural factors, which are measured by diverging methods. Given this complexity, a grading system and a normalization system offered two avenues for processing and integrating the different variables measuring development demands and land suitability [57,58].

An application test together with a literature review in the pre-study showed that the results after normalization were able to precisely reflect the relative position of the value of the assessed object within a specific range [69–71]. However, the disadvantage is that after normalization, the objective and realistic meaning of this range, including all the values of the assessed objects, was no longer reflected [57]. For example, when LST values of the two groups of objects are uniformly distributed in the range of 11–20 °C and 21–30 °C, the results obtained by normalization methods such as min-max or Z-score are the same, but the intensity levels of HIEM demands for the two groups are significantly different. The conclusion is that the normalization system is more suitable for comparing and analyzing the variation and interaction among different variables. However, in practice, there is a risk of homogenizing or reducing the difference between different UBGI demands with different urgency levels for planning [58,70]. Additionally, it is difficult to normalize policy-related, societal, and cultural factors that must be considered in a comprehensive planning project [43]. Consequently, the grading system, which is more balanced, compatible, and comprehensive [55,60], was adopted in this study.

The grading system applied in assessments of land suitability [58], ecological sensitivity [57], and supply–demand for UBGI [54] must be informed by existing research in different fields [43,55]. This will give a more realistic picture of demand intensity and the land suitability, and make results more legible and comparable. In the case of Hekou, the assessment results demonstrated that the urgency of responding to the demands of ECP, SMD, and ROC are much higher than for HIEM, PVE, and CII, which is totally consistent with the feedback of the stakeholders obtained in the field investigation. These results allow for the efficient allocation of public resources in the process of structuring corridors and positioning hubs.

To simplify the layout optimization process while deploying PSTLIO, UBGI spatial layout optimization was redefined as a process of redistributing public resources in space according to demand–supply relationships. In this way, the complex factors affecting the layout optimization of UBGI could be classified into two types. The first comprises those factors that generate and influence UBGI demands, such as land use structure and resident distribution. The second includes factors that determine the supply of land and potential for UBGI development of a city (e.g., city renewal policy, the physical conditions of particular sites, etc.). Demand and supply patterns in a city could be individually identified and compared in PSTLIO to further the optimization of UBGI layouts.

In Hekou, we considered six types of demand and six variables of land suitability with PSTLIO, but the modeling approach of PSTLIO is compatible, flexible, and allows for additional demands and variables. For future iterations of the tool, additional UBGI development demands, such as emergency shelter, air purification, and noise reduction, can be integrated into the tool, and demands that prove less significant could be replaced. Moreover, the assessment variables in the tool can be further expanded and the indicators can be subdivided at a more detailed level.

The study showed that PSTLIO can serve more than one function. Assessment results not only played a key role in the decision-making process for UBGI layout formulation, but they also provided direct support for defining the class and the function of each UBGI component. Moreover, the information regarding the intensities of the different development demands could guide the future design of each component (e.g., in the processes of programming and facility selection and installation).

The application of PSTLIO has certain limitations, such as determining the distribution of UBI and UGI. The absence of some basic data also led to limitations in the assessments of the case study. For example, the lack of detailed data on the quality of the air, soil, and water in different areas of Hekou influenced the integrity of the assessments of the demand criteria for environmental services. Compared to the tools focusing on the precise analysis of the UBGI services on a small scale [21,72], there are also spatial limitations to PSTLIO. In this study, PSTLIO was able to provide guidance for effectively laying out and optimizing UBGI at the macro-scale. However, limited by the accuracy and granularity of the data in Hekou, comparatively little could be done with PSTLIO at the micro-scale to help plan small UBGI components, such as pocket parks, roof greening, and rainwater storage tanks. Nevertheless, due to their ease of installation and their cumulative effect once deployed one a large scale, UBI and UGI at the micro-scale are today considered to be as important as large-scale components, especially in high density environments. In light of their importance, this study points to the need to improve support technology and to further theories of layout formulation.

6. Conclusions

This case study in Hekou provides critical insight into the UBGI planning stage, but it also demonstrates the benefits offered by PSTLIO in UBGI integral layout optimization. According to the results obtained from applying PSTLIO in Hekou, PSTLIO's contributions to the planning process could be grouped into three main categories:

1. Firstly, a platform was built to investigate and identify the different service demands for UBGI, and to understand the determining factors and distribution patterns of each service demand. The platform also facilitated the process of prioritizing responses to diverse service demands. This directly supports decision-making when service demands are thoroughly mixed in high-density areas.
2. Second, land supply potential for UBGI development in a city could be integrally analyzed in PSTLIO. Factors regarding urban development policy and existing physical conditions that could affect land supply for UBGI development were taken into account in assessments of land suitability. On this basis, future layout proposals would be guaranteed greater adaptability to urban context.
3. Thirdly, a PSTLIO-based solution was developed to structure the link network and hub system, define the functions and service patterns, and help regulate the scale of each component of UBGI.

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