Ecological Indicators 136 (2022) 108714

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Construction and optimization of ecological security patterns based on social equity perspective: A case study in Wuhan, China

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ARTICLE INFO

Keywords:
Ecological security patterns
Social equity
Minimum cumulative resistance
Buffer analysis
Wuhan

ABSTRACT

Ecological Security Patterns (ESPs) are important nature-based solutions for ecological problems caused by urbanization and industrialization. Previous studies on ESPs focus on natural conditions only, yet do not incorporate the need for social equity. This study aims to address this quandary for the study area of Wuhan by identifying and extracting ecological sources and ecological corridors, followed by an ecological sensitivity assessment, minimum cumulative resistance model and buffer analysis, in order to construct and optimize ecological security patterns. The optimization for the construction of the most suitable ecological security patterns relies on social equity aspects, including the quality of urban ecological services and the improvement of the well-being of urban residents. The results demonstrate: (1) There are 19 ecological sources in Wuhan and 51 ecological corridors with a total length of 840.10 km. (2) To cater for the optimization of social equity needs, it was necessary to add one additional amendment source, with an area of 14.89 km^2, and 25 new amendment corridors with a total length of 287.8 km. (3) Optimizing the ecological security patterns in Wuhan is possible through the derivation of an ecological restoration area, ecological improvement area, ecological control area and ecological shield area. The results indicate the feasibility of simultaneously protecting urban ecological security and realizing social equity.

1. Introduction

The advancement of economic development and associated spatial demographic changes has led to both rapid urbanization and pressure on the ecological environment in China. The rapid expansion of urban space has extremely squeezed the natural ecological space (Kang et al., 2021; Peng et al., 2018). Additionally, problems such as environmental degradation, species decline and soil erosion caused by the over-exploitation of resources still exist (Xu et al., 2019; Li et al., 2020a,b; Han et al., 2021; Wu et al., 2021). Given these challenges, the Chinese government is currently prioritizing policies based on ecological principles, evidenced by recent achievements in environmental conservation by implementing high-quality development strategies and promoting ecological protection and restoration. In 2020, the nine binding targets on the ecological environment and the phased tasks for tackling key problems of pollution prevention, which set out in 13th five-year plan for Economic and Social Development of the People's Republic of China, were completed according to plans. Furthermore, the legal system has also been adapted to incorporate the ecological principles in order to achieve the ecologically oriented policy goals. Despite these adaptations there are still problems of pollution and ecological damage in local areas (Peng and Zhou, 2019; Wu et al., 2021). This requires new goals for an ecologically responsive spatial development. Hereby, it is necessary to optimize the both spatial development goals, whilst building and protecting a more solid ecological security barrier. Based on this, the construction of a continuous, complete and systematic Ecological Security Patterns (ESPs) has become the key to further guarantee ecological security (Jiang et al., 2021; Jin et al., 2021).

ESPs are mainly composed of landscape elements in different spatial locations. ESPs reflect a spatial configuration scheme for maintaining the continuity and stability of regional ecological safety from the principle of optimization of comprehensive benefits, and in response to regional ecological environment problems (Li et al., 2019; Wang et al., 2021a, Wang et al., 2021b). In recent years, the Chinese government discovered the importance of ESPs for aligning economic development and ecological protection, and therefore gradually enhanced the role of ESPs in their environmental policies. In 2012, the report of the 18th National Congress of the Communist Party of China proposed to build an

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https://doi.org/10.1016/j.ecolind.2022.108714
Received 23 December 2021; Received in revised form 19 February 2022; Accepted 21 February 2022
Available online 25 February 2022

ESP to promote an ecologically response development. In 2017, the Outline of China's Territorial Planning (2016–2030) made this intention more concrete by formulating a multi-level and multi-scale ESP framework. In 2020, 14th Five-Year Plan for Economic and Social Development of the People's Republic of China listed building an ESP as one of the three major strategies for spatial development and protection of the national territory. Currently, building ESPs has become a core instrument to resolve the contradictory goals of between ecological protection and economic development, guarantee ecological security and human benefits, and promote ecological principles (Huang et al., 2021; Yue et al., 2019).

The construction of ESPs does not only protect urban ecological security, but also aims to foster ecological welfare for urban residents (Zhang et al., 2017; Wang and Pan, 2019; Kmail and Onyango, 2020; Fan et al., 2021). Still, however, there appears to be an imbalance between urban social spaces and urban ecological spaces (Wolff et al., 2020; Zhang et al., 2021). Some scholars note the inequality in urban residents' access to urban green spaces (Chen et al., 2020; Li et al., 2021a,b,c; Wu and Kim, 2021), urban parks (Li et al., 2021a,b,c; Wang et al., 2021a, Wang et al., 2021b), and green services (Wang et al., 2018). Hence, a more equitable distribution is urgent. As ESPs usually cover ecological landscape elements such as green spaces and parks (Xiao et al., 2020; Yin et al., 2020), it is worth considering ESPs to supply ecosystem services and enhance the equity of residents' ecological benefits. In other words, the construction and evaluation of ESPs has the potential to support the creation of more urban environmental equity. Furthermore, the concept of fairness and justice has long been integrated into the development of Chinese society. In ancient China, there was a thought of "Inequality, not scarcity, that persecutes governors", and now it has expanded the basic principle of "People-oriented, fair sharing". In view of this, the construction of ESPs needs to align with building social equity, that is, urban residents should enjoy ecological space as fairly as possible. Given this, the key question of this research is: how to construct the urban ESPs, conceptually and methodologically? This includes the question on how to optimize ESPs to ensure social equity. These scientific questions are relevant in the discourse on social and spatial equity on the one hand and spatial and environmental justice, on the other hand (Heckert and Rosan, 2018; Uwayezu and de Vries, 2020).

There are a number of previous studies on the conceptualization of ESPs and methodology to construct ESPs. For example, Xu et al. (2019) use Wenchuan County as an example to construct an ESP in order to improve the sustainability of a nature reserve landscape; Liu et al. (2020a,b) derives how and ESP framework based on the value of ecosystem services helps to achieve sustainable management of the ecosystem in Zhuhai, China. This research posits that the basic paradigm of "identifying ecological sources - constructing resistance surfaces - extracting ecological corridors" informs how to construct an ESP. Additionally, there are studies focusing on the type of optimization of ecological security patterns. Reason from optimizing biodiversity conservation (Delmas et al., 2019) aim at optimizing ecological restoration of land space (Li et al., 2021a,b,c) on optimizing urban growth boundary optimization (Yin et al., 2020). Hence, there is a large theoretical variety of optimizing the ESPs. What is however lacking in all of these studies is a more mature theoretical system from the perspective of social equity. Without the consideration of people's needs and interests and an-orientation towards fair sharing of resources, any ecological security strategy is likely to contradict the pursuit for a better living environment. This justifies a more detailed research on optimizing methods for ESPs. To test the ideas of optimized ESPs we selected Wuhan city as a study area. Geographically, it is rich in mountain and water resources, and as a study area it fits the characteristics of having contradicting needs in terms of economic and ecological patterns, and possible social inequities when opting for one optimization strategy. The alternative multi-dimensional optimization can therefore be tested and validated in this area. Specifics are provided in the subsequent section.

2. Methodology

2.1. Study area

Wuhan is located in the east of Hubei Province, China. The city has 13 administrative districts with a total area of 8,569.15 km^2 (Fig. 1). Wuhan is rich in natural resources such as lakes, wetlands and forests. However, economic development has fostered urbanization and changed the city to favor an industrial spatial structure at the expense of ecological space. In recent years, the Wuhan government has increasingly aim to adhere to more ecological principles for its development. This includes a policy strategy for configuring ecological water networks, construction of parks and green spaces, and public campaigns for embracing the blue sky. Still, however, most of the ecological spaces in Wuhan are fragmented and there is a lack of spatial continuity. It is therefore urgent to construct systematic, multi-level, continuous and integrated ecological security patterns which connect various ecological protection areas in an integrated manner.Fig. 2

2.2. Data sources

This study utilized the following data (1) Digital elevation data in raster format and MODIS data, derived from the geospatial data cloud (http://www.gscloud.cn/), a professional service platform built and operated by computer network information center of the Chinese Academy of Sciences. The MODIS data were mainly used to extract NDVI values and to estimate the vegetation cover. (2) Land cover data derived from GlobeLand30 (http://www.globallandcover.com/). These data are a product of the 863 Program's global land cover mapping and key technologies research program. (3) Vector data of water, roads and residential spot, extracted from the Open Street Map platform. (4) Industrial points of interest, obtained from the OSPIDER. (5) Administrative area vector data, obtained from the OMAP platform (Table 1).

2.3. Research methods

2.3.1. Ecological sensitivity assessment (ESA)

Ecological sensitivity refers to the ability of ecological factors to adapt to external pressure or human disturbance when the environmental quality does not decrease. Specifically, this method first constructs the index system and assigns a weight to each index, then superposes and analyzes each ecological factor, and finally obtains the ecological sensitivity distribution of a region in space. Equation (1) summarizes this sequence (Yang et al., 2002).

$$S = \sum_{i=1}^{n} Vi \cdot Wi \tag{1}$$

In this equation S is the comprehensive score of ecological sensitivity, N is the number of single ecological factors, V_i is the score of the i^{th} ecological factors, and W_i is the weight of single ecological factors.

In this study, we employ the ecological sensitivity assessment method to identify ecological sources. Ecological sources are patches with high quality of ecological services that are beneficial to maintaining biodiversity and ecosystem stability in the region (Wu et al., 2013).

Considering the ecological characteristics of Wuhan and the applicability of the data, a total of six ecological factors were selected (Table 2). According to the National Ecological Function Zoning issued by the Ministry of Environmental Protection of China in 2015 (No.61 of 2015), the elevation, slope grade and topography indicate the level of ecosystem functions of water conservation and soil maintenance in the study area, the vegetation coverage and distance from water areas indicate the level of ecosystem functions of residential protection in the area, and the land cover indicates the distribution of ecosystems and the level of ecosystem functions of product supply in the area. Combined with analytic hierarchy process (CR = 0.0327 < 0.1, pass the test) to

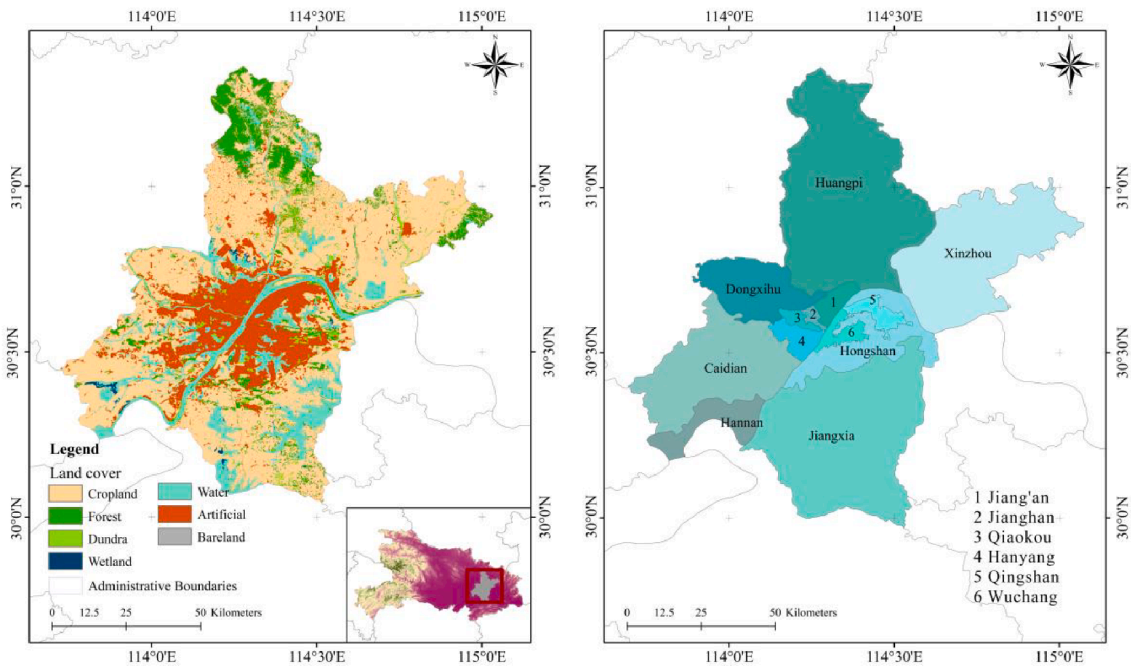

Fig. 1. Location map of Wuhan city.

determine the weight of each factor.

The analysis is mainly carried out using geospatial techniques, which are widely used in the field of spatial planning (de Vries, 2022). In this study it is mainly implemented through ArcMap 10.8 software (ESRI, Inc., Redlands, CA, USA). The first step was to derive the ecological sensitivity of single factors. This required using the tools of mosaicing, clipping, Euclidean distance calculation and reclassification after which it was possible to assign corresponding ecological sensitivity scores to six single ecological factors: elevation, slope, topography, vegetation, hydrology and land use type. This enabled drawing the ecological sensitivity evaluation results of single factors. The next step was to conduct, a comprehensive evaluation analysis of ecological sensitivity, by superimposing the results of ecological sensitivity analysis of single factor and using the tools of weighted synthesis and grid calculator. Finally, taking into account the description of ecological sensitivity classification in the National Ecological Function Zoning issued by the Ministry of Environmental Protection of China in 2015 (No.61 of 2015) and related studies (Huang et al., 2020; Jin et al., 2021; Lin et al., 2021), the comprehensive score was divided into five sections: non-sensitivity, mild sensitivity, moderate sensitivity, highly sensitivity and extremely sensitivity. With these results it was possible to draw, a comprehensive evaluation map of ecological sensitivity in Wuhan.

2.3.2. Minimum cumulative resistance model

The Minimum Cumulative Resistance (MCR) model enables the calculation of the total cost of the spatial movement of a certain species from its original source to other target points. Specifically, this method needs to construct the ESP index system and assign each index weight, followed by a superposition analysis of each resistance factor. Finally, one can obtain the resistance distribution of a region in space, using formula (2) (Knaapen et al, 1992; Yu, 1999).

$$R = \sum_{i=1}^{n} (Hi \bullet Wi) \tag{2}$$

here, R is the comprehensive resistance value, n is the number of resistance factors, H_i is the score of the i^{th} resistance factor and W_i is the weight of the i^{th} resistance factor.

In this study, we used the MCR model to extract ecological corridors. Ecological corridors are important ecological channels for the exchange and flow of species in the region, which is of great significance to the protection of biodiversity and ecological services (Zhu et al., 2005).

Calculating the resistance surface follows two steps. The first step is to select the resistance factors. Considering the natural, economic and social conditions of the study area and the applicability of the data, we opted for eight resistance factors: elevation, slope grade, vegetation cover, land cover, distance from water areas, road, residential areas and industrial points. Among these, elevation, slope, vegetation cover, land cover and distance from water areas are natural resistance factors; contrastingly, distance from road, residential areas and industrial areas are social resistance factors. Using an analytic hierarchy process ($CR = 0.0238 < 0.1$, pass the test), the weight of each factor could be assigned. Table 3 presents the results of this process.

The second step was to create the resistance surface. This step relied on using the tools of reclassification, and raster calculator by ArcMap10.8 software, which generated a single resistance surface and a comprehensive resistance surface. Based on the identified ecological sources and the comprehensive resistance surface, the ecological corridors were extracted by using the tools of cost distance and cost path.

2.3.3. The buffer analysis method

The buffer analysis method is a widely-used tool to analyze spatial influence factors. It requires setting up an influence area around the target point, line and plane according to the given distance, and then analyze the spatial influence of the object (Zhao et al., 2005). In this study, we used the buffer analysis method to analyze the impact range of ecological sources and ecological corridors, and then optimize the ESPs based on the principle of social equity.

The first requirement when establishing a buffer is to determine the impact area of the object, i.e., the buffer distance. We chose the daily travel distance of residents to represent the impact radius of ecological sources and ecological corridors in order to ensure that residents enjoy higher ecological accessibility. With regard to the daily travel distance of residents, this study relied on the concept of “15-minute life circle”. This concept reflects the inclusion of relatively perfect set of public facilities for daily needs of residents within a 15-minute walking range (Cheng, 2018). Wu et al. (2020) argues that the travel distance of the 15-minute life circle is approximately 800 m-1100 m. This distance range is

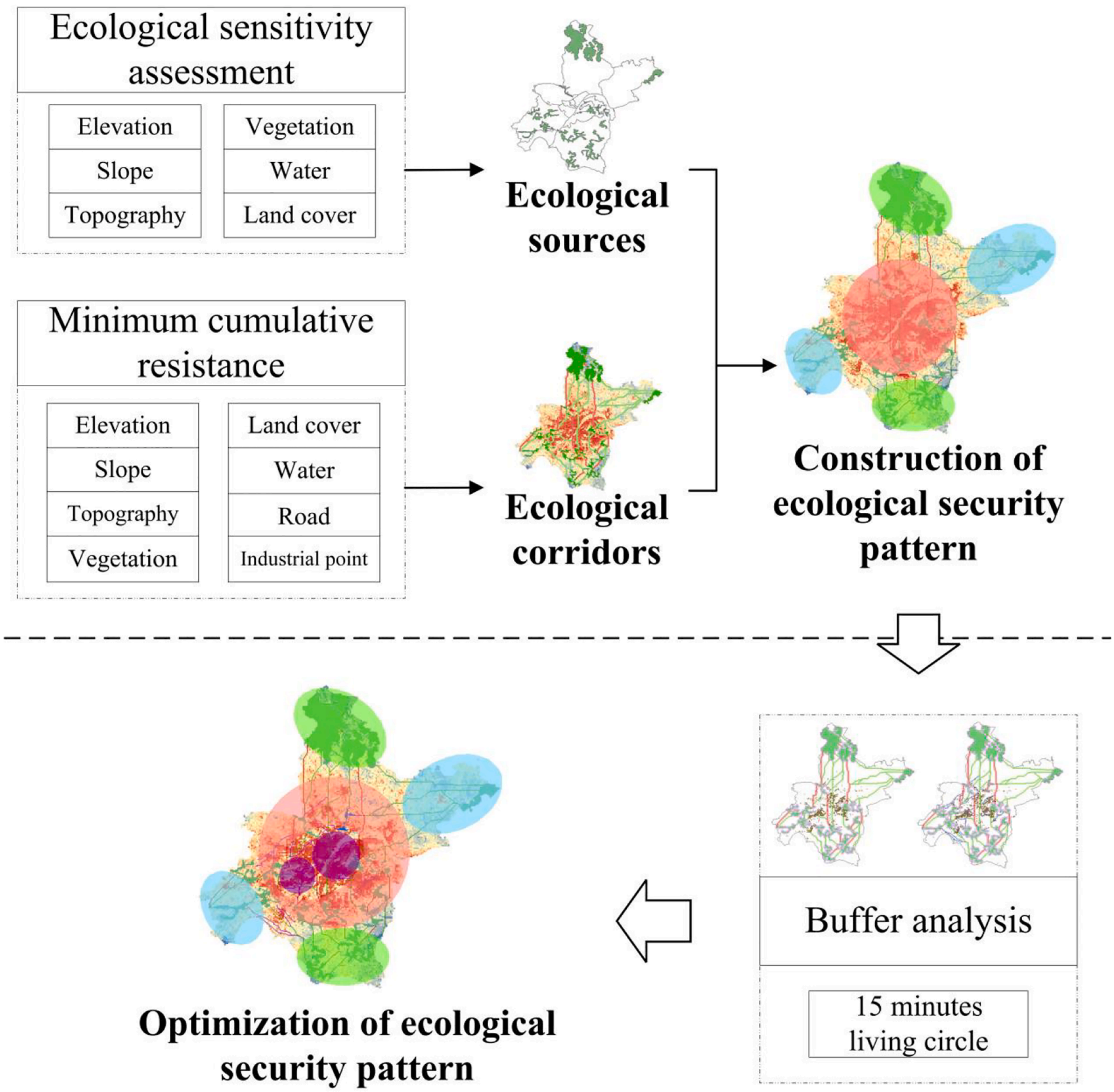

Fig. 2. Workflow of construction and optimization of ESPs.

Table 1
Data description and source.

Data name	Data type	Data source	Time
Administrative boundaries	Vector	OMAP	
Elevation	Raster	Geospatial data cloud	
Water areas	Vector	Open Street Map	2020
Land cover	Raster	GlobeLand30	2020
MODIS	Raster	NASA	2020
Road	Vector	Open Street Map	2020
Industrial point	Point of Interest	OSpider	2020
Residential areas	Vector	Open Street Map	2020

therefore a representative buffer distances, and can be utilized in the further analysis. So, we chose for (1) Sources: the buffer radius of the ecological sources and amendment sources are 1100 m and 800 m respectively. (2) Corridors: the buffer radius of important ecological corridors, normal ecological corridors and amendment corridors are 1100 m, 950 m and 800 m respectively.

3. Results and analysis

3.1. Identification of ecological sources

3.1.1. Results of ecological sensitivity assessment

From the assessment results of the single ecological factors, (Fig. 3 (a)) demonstrates that the higher elevation areas in the northern part of the study area have a higher ecological sensitivity (highly sensitivity or extremely sensitivity). This area mainly includes the Shuangfeng Mountain Area in the northwest of Huangpi District. Fig. 3(b) shows that the undulation factor generates a higher ecological sensitivity in the northern, northeastern and south-central parts of the study area, which mainly includes the hilly and wooded areas in the northwestern and central parts of the Huangpi District. In terms of slope factor, represented in Fig. 3(c), the north, northeast, southwest and south-central areas of the study area have higher ecological sensitivity. This mainly includes the mountainous and woodland areas in the northeast of Xinzhou District, Eastern Hongshan District, Northern Huangpi District, Central Jiangxia District and northwestern Caidian District. With regard to the vegetation cover factor, Fig. 3(d) indicates that, the northern,

Table 2
Index system of ecological sensitivity assessment.

Ecological factor (Unit)	Weight	Sensitivity				
		Non-sensitivity	Mild sensitivity	Moderate sensitivity	Highly sensitivity	Extremely sensitivity
Elevation(m)	0.1121	−60 ~ 40	40 ~ 90	90 ~ 190	190 ~ 360	> 360
Slope grade (°)	0.0693	0 ~ 25	25 ~ 45	45 ~ 60	60 ~ 75	> 75
Topography(m)	0.0864	0 ~ 10	10 ~ 25	25 ~ 50	50 ~ 85	> 85
Vegetationcoverage	0.3123	0.00 ~ 0.25	0.25 ~ 0.50	0.50 ~ 0.70	0.70 ~ 0.80	> 0.80
Distance fromwater areas(m)	0.1702	> 900	500 ~ 900	300 ~ 500	100 ~ 300	< 100
Land cover	0.2497	artificial	bare land	cropland, tundra	grassland, wetland	forests, water

Table 3
Index system of resistance factors.

Resistance factor (Unit)		Weight	Resistance value				
			1	2	3	4	5
Natural factor (Unit)	Elevation(m)	0.0698	−60 ~ 40	40 ~ 90	90 ~ 190	190 ~ 360	> 360
	Slope grade (°)	0.0698	0 ~ 25	25 ~ 45	45 ~ 60	60 ~ 75	> 75
	Vegetation coverage	0.1617	> 0.80	0.70 ~ 0.80	0.50 ~ 0.70	0.25 ~ 0.50	0.00 ~ 0.25
	Distance from water areas (m)	0.0865	< 100	100 ~ 300	300 ~ 500	500 ~ 900	> 900
	Land cover	0.2411	forests, water	grassland, wetland	cropland, tundra	bare land	artificial
Man-made Factor (Unit)	Distance from roads (m)	0.0905	>700	350 ~ 700	200 ~ 350	100 ~ 200	<100
	Distance from industrial point (m)	0.1452	>2200	1300 ~ 2200	700 ~ 1300	300 ~ 700	< 300
	Distance from residential spot (m)	0.1354	> 450	300 ~ 450	200 ~ 300	100 ~ 200	<100

northeastern and southern parts of the study area have a relatively high ecological sensitivity (high sensitivity). These areas mainly include the woodlands in the northwestern part of Xinzhou District and the arable lands in the southern part of Jiangxia District. In terms of water factor, represented by Fig. 3(e), the central, southern and southwestern parts of the study area indicate a higher ecological sensitivity, mainly due to the interweaving of rivers and numerous lakes in the region. In terms of land cover factor, Fig. 3(f) shows that the northern part of the study area has a higher ecological sensitivity, mainly due to the woodlands in northern Huangpi District.

According to the comprehensive results of ecological sensitivity assessment (Fig. 3(g)), the area which is highly and extremely sensitivity amounts to 1678.76 km^2, which accounts for 19.6% of the total area. Specifically, the highly and the extremely sensitivity areas include: (1) The mountainous areas in the north of Huangpi District, which has mountains such as Mulan Mountain and Yunwu Mountain, dominated by woodland, with a large vegetation cover and a good ecological environment. (2) The southern area of the Jiangxia District, where agriculture is well-developed, mainly consisting of cotton, vegetables and grain crops. This has therefore a relatively high ecological sensitivity. (3) The eastern part of Xinzhou District is mostly mountainous, which are dominated by woodland with a good habitat quality. In addition, the level of ecological sensitivity in the central part of the study area is relatively low, including the Jianghan, Qiaokou, Jiang'an, Hanyang, Wuchang, Hongshan and Qingshan Districts. The land cover in these areas is mainly construction land, with a small watershed area, low vegetation coverage, a high degree of interference by human activities, and a relatively poor ecological environment.

3.1.2. Identification of ecological sources

Based on the results of ecological sensitivity assessment and the natural, economic and social conditions in Wuhan, it was possible to identify the ecological sources. Firstly, one needs to select, the area where the ecological sources are located. This is based on the ecological sensitivity evaluation results, and using the principle of easy identification. This yielded 19 ecological sources, with a total area of 1033.82 km^2, accounting for 12.06% of the total area of the study area. The spatial distribution of ecological sources seemed scattered, except for the northern part of the study area, where ecological sources appeared more complete. In other areas the ecological sources were more fragmented. Fig. 3(h) presents the distribution of ecological sources in the 13 administrative regions, except for the five administrative regions of Jiang'an, Dongxihu, Jianghan, Qiaokou and Hanyang District.

3.2. Identification of ecological corridor

3.2.1. Establishment of resistance surface

The comprehensive resistance surface in Fig. 4 shows that the resistance values in the central, central south and central west of the study area are high, with an overall pattern of "Central dense and scattered around".

Among them, "Central dense" mainly involves the seven administrative regions of Jianghan, Jiang'an, Qiaokou, Hanyang, Hongshan, Wuchang and Qingshan District. These areas have dense road networks and a large population density, and are subject to a high degree of human activity interference. "Scattered around" mainly covers the north of Jiangxia District, the southwest of Huangpi District, the east of Caidian District and the southwest of Xinzhou District, the areas with higher resistance values in the four districts are all close to the economically developed areas in central Wuhan, which are significantly affected by road network extension and human disturbance.

3.2.2. Corridors extraction

A total of 51 ecological corridors with a cumulative length of 840.1 km were identified, including 12 important corridors (Fig. 4). Because of the large area of the study area, most of the ecological corridors are long in length and show relatively dispersed characteristics in space. Specifically, the ecological corridors are more densely distributed in the north, southeast and southwest of the study area. These regions are rich in natural resources such as lakes, reservoirs and mountains, and have high ecological environment quality, which provides the necessary conditions for promoting species exchange and migration.

3.3. Construction and optimization of ecological security patterns

3.3.1. Construction of ecological security patterns

The method of ecological sensitivity assessment enabled to identify 19 ecological sources and 51 ecological corridors, extracted by establishing a comprehensive resistance surface in the study area through the MCR model. Finally, based on the above results, it was possible to construct the patterns of ecological security in Wuhan. Three types of ecological protection zones were planned, namely, an ecological

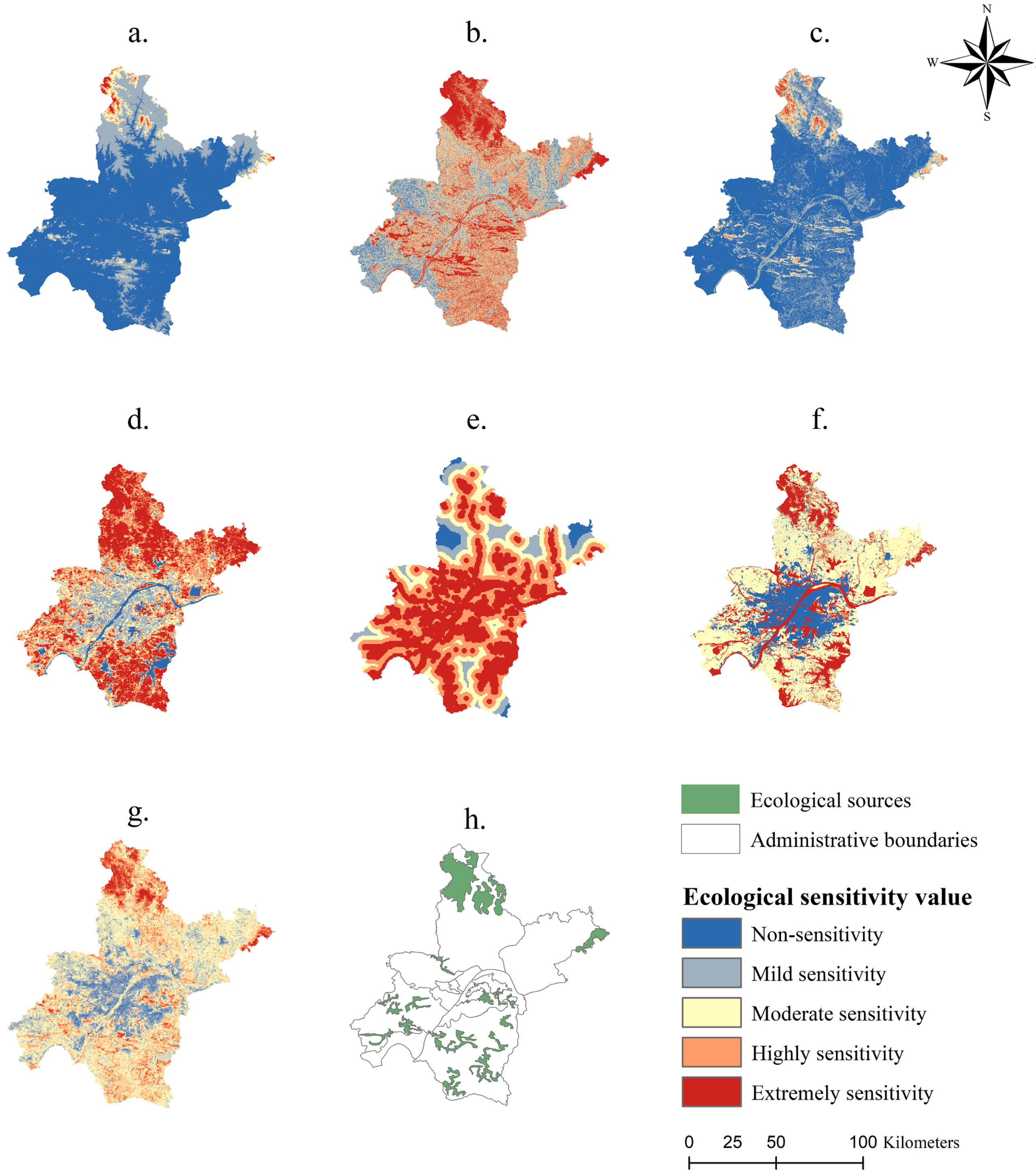

Fig. 3. Ecological sensitivity assessment and ecological sources. (a) Elevation. (b) Topography. (c) Slope grade. (d) Vegetation cover. (e) Distance from the water. (f) Land cover. (g) Comprehensive results of ecological sensitivity assessment. (h) 19 ecological sources with an area of 1033.82 km^2, accounting for 12.06% of the total area of Wuhan.

remediation area, an ecological control area and an ecological shield area. Fig. 5(a) presents these targeted ecological protection measures according to the actual situation. The justifications for the three ecological protection zones include:

(1) The ecological remediation area mainly refers to the area in the central of the study area that needs to strengthen the ecological protection and the ecological construction. From the perspective of urban development, one could argue that because of the advantages of transportation, industry and culture, a broad range of human activities and interventions have severely affected the central region over a long period of time. Similarly, from the perspective of land cover analysis, construction land in the central region is proportionally high as compared to other land cover types. From the ecological sensitivity and resistance value, the ecological sensitivity and resistance value are higher in the central area. Therefore, the ecological environment quality in the central region is relatively weak, and the ecological rehabilitation work would need to be accelerated.

(2) The ecological control area is mainly in the northeast of Xinzhou

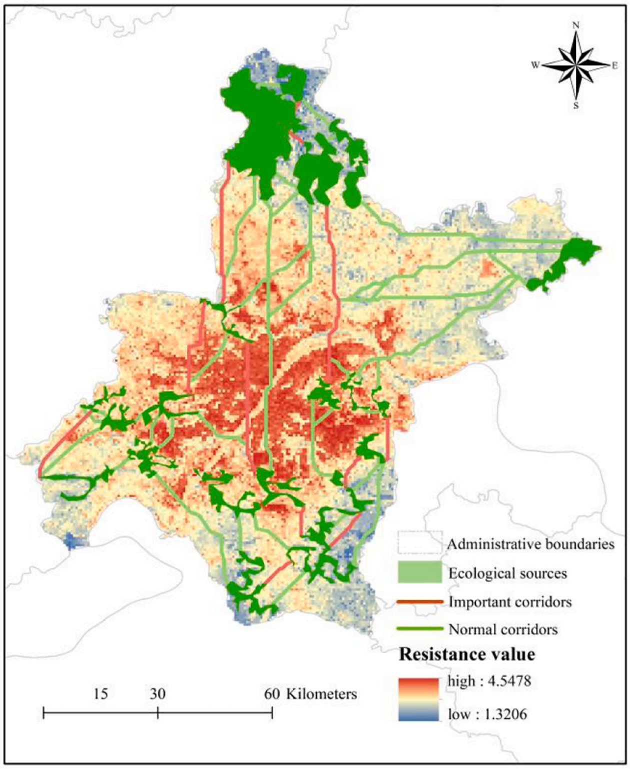

Fig. 4. Resistance surface and ecological corridors.

District, southeast of Caidian District and east of Hannan District. These areas one should continue to control the environment in the same manner as currently done. The economic strength of these three regions is however relatively weak and the population density is relatively low, but in the process of planning and development, the urban road network was gradually extended and the industries moved successively, which lead to higher ecological sensitivity yet also higher resistance values. There are many valuable ecological resources in this area, such as forestland, lakes and reservoirs. If these three regions were not controlled appropriately, the ecological environment quality of the region and the surrounding areas would be in danger.

(3) The ecological shield area refers to the regional space where an ecosystem is relatively stable and is conducive to maintaining the ecological security of the whole large region (Chen, 2002). The ecological shield areas mainly comprise of the northern Huangpi District and the southern Jiangxia District. These two regions are rich in forestland, lakes and reservoirs. They have good ecological functions, and are of great significance to the improvement of the ecological environment of the surrounding areas and even the whole of Wuhan.

3.3.2. Optimization of ecological security patterns

From the perspective of social equity, buffer analysis of ecological sources and ecological corridors was conducted, based on the constructed ESPs, followed by overlapping the buffering results with the distribution of residential areas in the study area. This yielded the extent of coverage of the existing ecological sources and the ecological corridors around the residential spots. As can be seen from the Fig. 5(b), the coverage of the ecological impact in the central part and the southwest part of the study area is relatively low, whilst the coverage of the ecological impact in other areas is relatively good. In other words, within the “15-minute living circle”, people living in central and south-central Wuhan will not be able to enjoy the ecological benefits brought about by the constructed ESPs. It is simply too far from the ecological sources and ecological corridors. Therefore, the constructed ESPs of Wuhan is limited with regard to the social equity indicator. It is difficult for many urban residents to get close to ecological sources and ecological corridors. This is therefore an issue which requires further optimization.

Based on the residential areas that cannot be covered by the impact area of the source corridor, parcels with high ecological sensitivity were selected as amendment sources, and paths with low resistance values and coherence were selected as amendment corridors. After optimization, an amendment ecological source of 14.89 km^2, 25 amendment ecological corridors with a total length of 287.8 km were added to construct the ecological security optimization pattern (Fig. 6(a)). Among

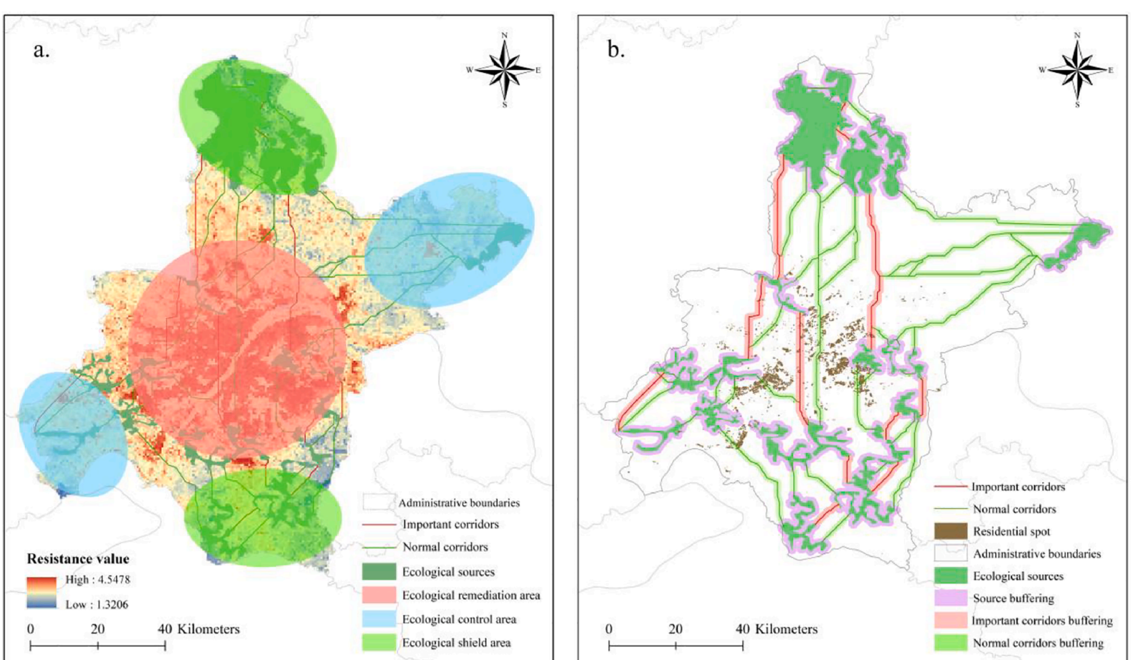

Fig. 5. Ecological security patterns of Wuhan city. (a) Ecological security patterns of Wuhan, consists of three types of ecological zones, 19 ecological sources and 51 corridors. (b) Buffer coverage condition of ecological security patterns.

them, the amendment source is located at the confluence of the Sheshui and the Yangtze River, and its ecological sensitivity assessment results are high or very high. Although the amendment source is relatively small, it is of great significance for the residents around it, so that they can enjoy the ecological space. Therefore, it is necessary to strengthen the ecological renovation of the fine patches, as it plays an important role in the ecological security of the surrounding area and possibly even in the whole area. In addition, the length of the amendment corridors is relatively short, and although they are low resistance paths with connectivity and relatively good habitat quality, their ecological status is still relatively fragile compared to the important corridors and the general corridors, they need to be further maintained and strengthened in the actual construction.

After the optimization of ecological security patterns, a certain number of ecological sources and corridors were added to ensure that residents in the study area can enjoy the results of the construction of ESPs and promote social equity. However, there are still areas in the study area, which are not covered by the impact radius of the ecological sources and ecological corridors (Fig. 6(b)). Based on this, and in order to further strengthen the ecological construction, this research once again demarcated the original ecological regulation area, and divided the former “Ecological remediation area” into two levels, namely an “Ecological restoration area” and an “Ecological improvement area”. This enabled to carry out the work of ecological protection with more pertinence.

4. Discussion

4.1. Comparison of related studies

Previous studies on ESPs have primarily focused on how to identify and construct ecological security patterns under existing habitat conditions, with an emphasis on “identification” and “construction”. For example, Li et al. (2021a,b,c) identifies ecological sources, corridors and nodes in the Chaohu Basin and construct ecological security patterns in the region. Jin et al. (2021) identifies and construct ecological corridors in Fengxian County, Jiangsu Province, based on ecosystem service functions and ecological sensitivity. Jiang et al. (2021) identify ecological sources, corridors and potential corridors in the Guangdong-Hong Kong-Macao Greater Bay Area in China based on the ecological background and ecological needs, and use them to construct the ecological security patterns in the region. However, relatively few studies optimize the ecological security patterns according to the actual needs, and include how to optimize it effectively. As urbanization continues, the ecological benefits of urban residents weakens by the encroachment of steel and concrete constructions. Yet, ecological benefits are crucial factors for public health, and the degree to which they can access these areas should also be fair. It is therefore necessary to accommodate these fairness norms in contemporary spatial planning.

This study highlights the importance of both “construction” and “optimization”, and provides a systematic planning tool to assess and design the overall ecological condition of the region. This tool focuses on the public requirement for fairness and equity in accessing ecological benefits, and optimizes the constructed ESPs. The optimized ESPs make the ecological condition of the study area more advanced, and yields a clearer treatment and restoration of ecological areas. It provides furthermore a systematic spatial support structure for urban residents to enjoy ecological space and obtain ecological benefits. This study further enriches the research related to the optimization of ESPs and provides a new perspective on the social equity of public access to ecological benefits.

Although this study contributes to the optimization of ESPs, there is still room for further improvement and extension of this research. For example, in the construction of ESPs, there could be more attention to the influence and impacts of choosing specific widths of corridors in the overall pattern. This may affect the variability of corridors within different regions. Therefore, how the width of ecological corridors creates new spatio-temporal changes is the direction of our future research.

4.2. Policy implications

Combining the results of the study and the actual ecological needs of Wuhan, one can derive a number of land and environmental policy recommendations. Firstly, in terms of natural conditions, the ecological

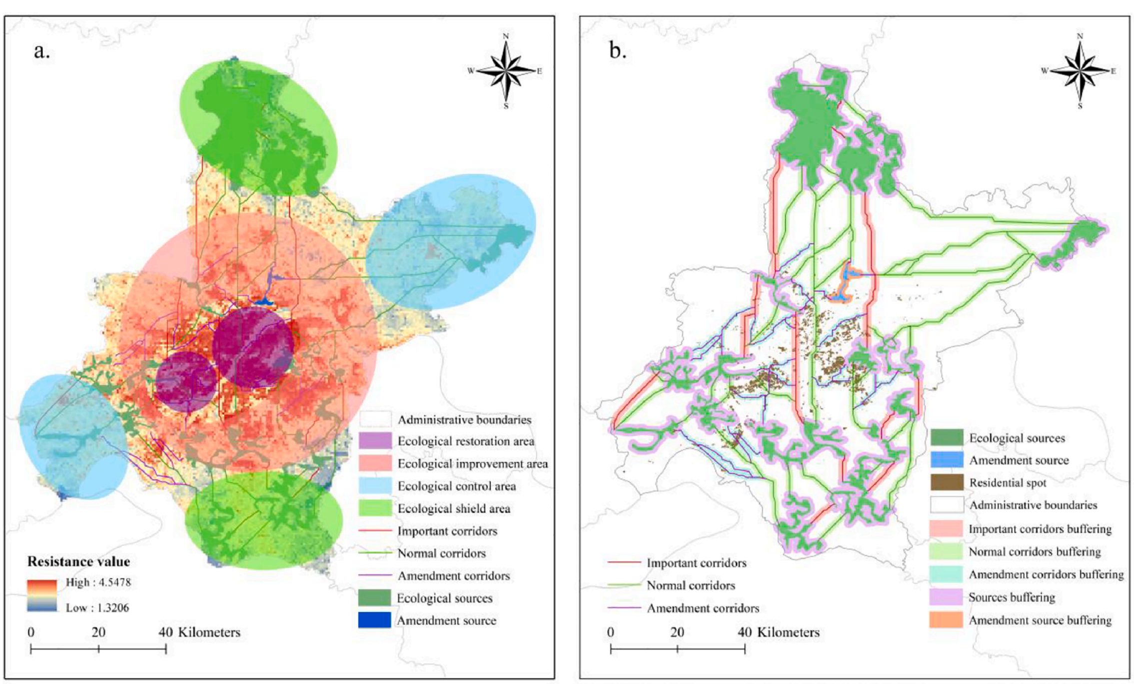

Fig. 6. Ecological security optimization pattern of Wuhan city. (a) Ecological security optimization pattern, consists of four types of ecological zones, 19 ecological sources and 51 corridors, 1 amendment source and 25 amendment corridors. (b) Buffer coverage condition after optimization of ESPs.

space in Wuhan is mainly distributed in a point-like manner and it lacks spatial continuity. This is not conducive to the maintenance and improvement of the overall ecological condition of the region on the one hand, and the protection of the ecological benefits of the public on the other. Secondly, in terms of social development, whilst the Wuhan government is planning to develop its secondary urban areas in the next five years, which are however in areas of a relatively fragile ecological habitat, there is an urgent need to re-consider how to strike a balance between development and ecological protection. Therefore, when considering the four ecological zones, we suggest specific policy actions for each of the following areas:

(1) For the ecological restoration area - the area in the central and the southwest-central part of the study area - it is currently not easy for the residents to obtain the ecological benefits, despite the optimization efforts. Therefore, additional stricter ecological restoration measures should be taken to secure ecological remediation. The ecological remediation areas mainly include Hanyang, Jiang'an and Jianghan District. Hanyang District is one of the cradles of modern industry in China, with a long history of industry and a relatively serious problem of ecological degradation. The Jiang'an District and Jianghan District are the areas with the most advanced economic development in Wuhan. Both districts have a large permanent population and tensions between people and land. So, the focus should be on strengthening the construction of ecological sources and ecological corridors connectivity, two types of measures should be taken respectively. First, professional ecological restoration measures should be taken for old industrial areas, such as increasing soil fertility and planting plants with the ability to absorb pollutants in heavily polluted areas. Secondly, for the overly dense residential areas, the entry point would be to optimize the human living environment, such as demolishing illegal structures to release space for ecological construction, or transforming abandoned building clusters into urban gardens.
(2) The ecological improvement area mainly consists of the area in the central part of the study area, except for the ecological remediation area. The ecological improvement areas mainly include Qiaokou, Dongxihu, Wuchang, Hongshan and Qingshan District. Among them, Qingshan District is one of the most important industrial areas in central China, whereas other districts are congested with people and buildings. Although the residents can enjoy a certain amount of ecological space, at the same time the number of accessible sources and corridors is relatively small. Hence, this area is the key area to optimize the ecological corridors. Specifically, the ecological improvement work should pay attention to the maintenance and improvement of the ecological corridors' habitat quality. Moreover, the improvement of ecological corridors can be started from behavior control in the new green areas, which would include a stricter supervision and punishment when observing illegal sewage discharge, excessive pumping of groundwater, illegal construction and other acts that damage urban ecology. Further preventive measures would be to set up as three-dimensional green belt, and planting a more diverse variety of green plants.
(3) For the ecological control area, the emphasis of ecological construction in this area would be control and improvement. In Wuhan's "14th five-year plan", it is proposed to "Make the main urban area better and four suburban areas stronger", of which the "four sub urban areas" are within the ecological control zone, indicating that under the situation of future key development, the ecological environment of the ecological control area will face great pressure. Therefore, it is necessary to take into account the basic conditions of ecological security and the carrying capacity of land resources, so as to control the deterioration of the regional ecological environment and take certain measures to improve the existing ecological environment. For example, to create urban ecological parks, change the wasteland into forest, etc.
(4) For the ecological shield area, the quality of the habitat in this area is already good enough, and the key point for the ecological construction is to maintain the current level of ecological quality. Yet, also here this would require a strengthening of environmental monitoring and protection, whilst additionally exploring further possibilities of ecological resources in the region. In this way, they can better support the functions of ecological services. For example, the water quality of lakes can be improved through intelligent measures such as the renovation of sewage networks and regular monitoring of water quality by drones, thus enhancing ecosystem stability.

5. Conclusions

The construction and optimization of the ecological security patterns is conducive to the simultaneous promotion of ecological protection and ecological benefits of residents. This study uses ecological sensitivity assessment, minimum cumulative resistance model and other methods to construct the ecological security patterns in Wuhan, and furthermore, from the perspective of social equity, combines buffer analysis method to optimize the ecological security patterns in Wuhan. The results of the study are as follows:

(1) Among the constructed ecological security patterns, there are 19 ecological sources, which is 1033.82 km^2, accounting for 12.06% of the total area of the study area, it presents the relatively scattered layout in the space. And there are 51 ecological corridors with a cumulative length of 840.1 km, including 12 important corridors, which are mainly distributed in the areas except the central part of the study area. The ecological security patterns can be divided into ecological remediation area, ecological control area and ecological shield area.
(2) From the perspective of social equity, there are differences in the supply of ecological space among constructed ecological security patterns, mainly because the ecological sources and ecological corridors in the central part of the study area and the southwest-central part of the study area are less in number and of poorer in quality, leading to inequity in the supply of ecological benefits.
(3) Through optimized ecological security patterns, one amendment source was added, with an area of 14.89 km^2, 25 amendment corridors were added, with a total length of 287.8 km. The original ecological remediation zone is refined into ecological restoration area and ecological management area. The optimized ecological security patterns better ensure social equity in the enjoyment of ecological space by local residents.

CRediT authorship contribution statement

Xufeng Cui: Conceptualization, Writing – review & editing, Resources, Supervision. **Wei Deng:** Methodology, Writing – original draft, Writing – review & editing, Visualization. **Jixin Yang:** Investigation, Writing – original draft, Writing – review & editing. **Wei Huang:** Investigation, Writing – review & editing, Formal analysis. **Walter T. de Vries:** Writing – review & editing, Supervision.

Declaration of Competing Interest

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

Acknowledgments

This work was supported by the Hubei Provincial Department of

Education Project of Philosophy and Social Sciences (CN) (No. 21G015) and the Project of Graduate Teaching and Education Reform (High−quality Teaching Cases), Zhongnan University of Economics and Law (CN) (No. JXAL202104).

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