Research Paper

Holistic Identification and Optimization of Basin Ecological Infrastructure Based on a Quantitative Analysis Framework

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Abstract

The river basin is the linking corridor between many cities in China, and the basin's ecological infrastructure is an important spatial pattern of regional ecological security. But in the actual planning work, qualitative research, directly choosing nature reserves, large parks, and water areas as ecological infrastructure, becomes the method most people use in basin ecological holistic analysis. It is empirical with lacking process analysis and tends to ignore small-scale ecological land use. Therefore, an analysis framework for evaluating the ecological importance of land use is needed to holistically analyse basin ecological infrastructure. This paper establishes a quantitative analysis framework based on a quantitative analysis of ESV. Quantitative analysis tools, such as the value equivalent method, circuit theory, and SCS model, are used to analyse the "land-water" ecological land use in the basin. And, Taihu County was taken to verify the feasibility and application effect of the quantitative analysis framework. The results show that the quantitative analysis framework has a better effect on the holistic identification of basin ecological infrastructure. In the case study, by the framework, this paper classifies three types of basin ecological infrastructure with different importance. The framework can be effectively combined with planning, and quantitative results can be conveniently used for planning.

Keywords

Basin Ecological Infrastructure; Quantitative Analysis; Holistic Identification; Optimization

1. Introduction

Ecological space has the function of providing ecological services and products and supports the sustainable development of human beings and the biosphere. The ecological pattern is the key to maintaining the integrity of the structure and function of ecological space. And a safe and complete ecological pattern can promote greatly development of the ecosystem service function of ecological space. China proposed to establish a territorial space planning system in 2019, and ecological space has become an important part of territorial planning. Ecological infrastructure (EI) refers to the ability of natural landscapes to support cities, which was proposed in the Man and Biosphere Programme (MAB) document by UNESCO in 1984. In terms of planning, the concept of EI is used in ecological network planning (Liu et al.,2005). Ecological infrastructure planning is to protect key ecological spaces with important ecological functions, which has become an important approach to constructing ecological patterns in China (Wang et al.,2022). Its basic theory is an ecological pattern in landscape ecology and gradually formed a research paradigm with ecological sources and corridors (Yu,1999). In ecological infrastructure planning, there are two previous studies about the selection of ecological sources. First, empirically divide into the scale range of ecological sources (Li et al.,2019). Second, take ecological land, such as various nature reserves, scenic spots, and large parks, as the ecological source (Liu et al.,2019; Tan and Yao,2015). It is qualitative and empirical, with lacking process analysis. The qualitative approach easily obtains coarse-grained ecological patterns and has a good practical effect on large scales. However, EI contains a variety of ecological factors, such as waterbody, mountains, forests, fields et al., and its ecological services are different at different scales. At the mesoscale and microscale, the qualitative method tends to ignore important small-scale ecological land use. Therefore, an analysis framework for evaluating the ecological importance of land use is needed to holistically analyse Ecological infrastructure.

Ecological infrastructure is the most important ecological pattern for regional ecological function. The “patch – corridor – matrix” theory provides an important theoretical basis for this paper. The theory is to study the ecological structure of different land use types, which is related to the contents of land use ecological importance in this paper. Ecological land supplies ecological products for humans, and its ecosystem service value (ESV) is a quantifiable indicator of analysing ecological importance. The Millennium Ecosystem Assessment report, released by the United Nations in 2005, puts forward the ecosystem service (ES) concept. ES is widely recognized internationally, and some scholars further quantify ecosystem services’ value by using eco-economic methods (Chen,2022). A series of quantitative studies are carried out based on ESV. For example, based on ESV some Chinese scholars conducted quantitative research on ecological spatial pattern evolution (Gao et al.,2021; Cheng et al.,2020; Xiao et al.,2019), which verifies the feasibility of quantitative research based on ESV. Ecosystem service value analysis provides a way for quantitative analysis in this study.

The river basin is the linking corridor between many cities in China, and the basin’s ecological infrastructure supports the ecological foundation of urban development. The holistic and systematic concept of basin protection has been widely accepted in China, and qualitative research becomes the method most people use in basin ecological holistic analysis. Therefore, based on the quantitative analysis of ESV, this paper builds a quantitative analysis framework of basin ecological infrastructure and applies this framework to a case study of the Taihu county basin. Quantitative analysis provides intuitive results of data, which can judge the ecological importance of land use in the basin more accurately and objectively. The framework can be effectively combined with planning, and the quantitative results can be conveniently used for planning.

2. Study area and data sources

2.1. Study area

The study area, Taihu county of Anhui province, is located within 115°45 '-- 116°30' east longitude and 30°09 '-- 30°46' North latitude. The county topography belongs to hilly and mountainous areas, with high terrain in the northwest and low terrain in the southeast. Due to its location in the North subtropical monsoon climate zone, the county has an average annual rainfall of 1368.4 mm and has plenty of rain in summer. There are 108 rivers in the county territory, and the main river is 81 kilometers long. Taihu County has a total of 15 towns (Figure 1) with a population of nearly 580,000 and its administrative area covers 2,040 square kilometers.

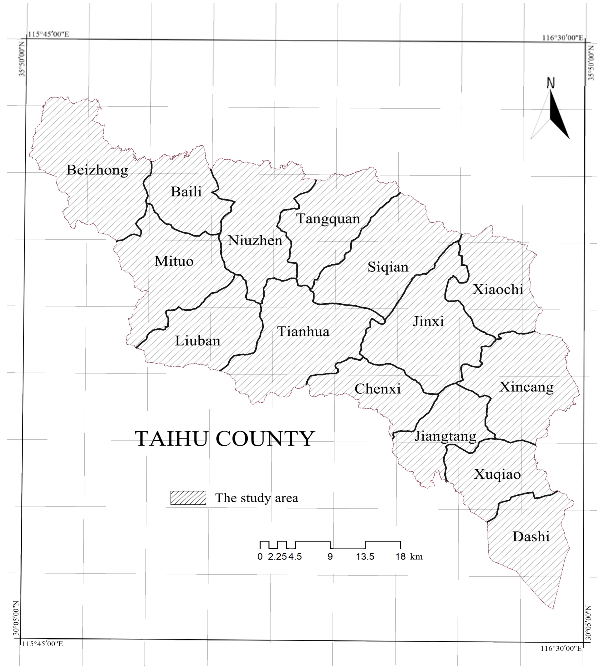


Figure 1. Taihu county administrative region. Source: author owner-drawing.

2.2. Data sources

The research data for the 2020 year can be easily obtained from government statistics and the geospatial data set of the Chinese Academy of Sciences. The administrative scope of Taihu is obtained from the second land survey data of Anqing City. The land use data comes from the data-sharing service platform of the Chinese Academy of Sciences. The land cover data for the 2020 year was selected with a resolution of 30m, that GIS was used to reclassify the land use types into six categories: waterbody, forestland, cropland, grassland, wetlands, construction land. DEM digital elevation data comes from the geospatial data cloud of the Chinese Academy of Sciences, with a resolution of 30m. The data on the main crops (grain, oil, and cotton) of Taihu is obtained from the Statistical Bulletin of National Economic and Social Development of it, and the data on national grain are obtained from the Statistical Bulletin of national agricultural Reclamation economic and Social Development. Extreme rainfall data are obtained from Taihu county annals and the official websites of Taihu and Anqing.

3. Analysis framework and methods

3.1. Quantitative analysis framework construction

Based on the quantitative analysis of ESV, this paper builds a quantitative analysis framework of basin ecological infrastructure (Figure 2). This paper builds a quantitative analysis framework including land and water. The value equivalent method is used to comprehensively evaluate geospatial value differences of basin ecological function for land and water. Based on the comprehensive evaluation, the circuit theory is used to analyze the ecological source and corridor of the land, and the SCS model is used to analyze the ecological pattern of the water. The quantitative results of the land and water are superimposed to form differences in the importance of basin ecological infrastructure. Finally, using the quantitative analysis framework, Taihu County is taken as a case study to verify the feasibility of the framework application.

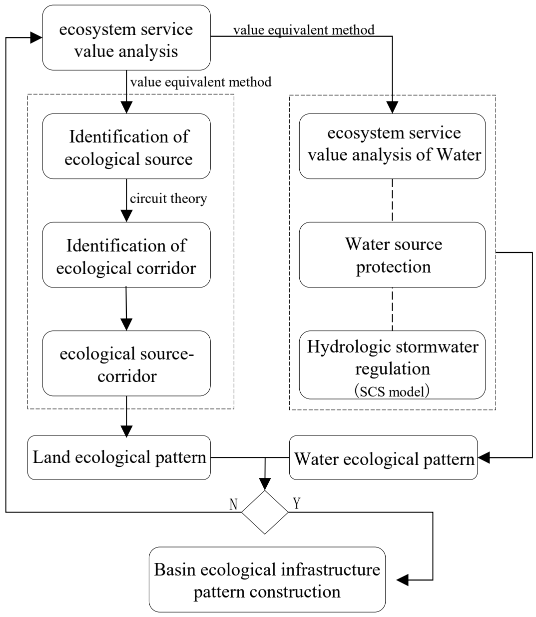


Figure 2. the quantitative analysis framework of basin ecological infrastructure.

Source: author owner-drawing.

3.2. Analysis method of ecological sources based on ESV

Ecosystem services (ES), proposed by the United Nations, include four functions (namely supply, regulation, support, and culture) and 11 detailed services (Ahmed,2002; Eigenbrod et al.,2011). Ecosystem service value (ESV) is a quantitative evaluation of the ecological economy based on ES. The value equivalent method, proposed by Xie (Xie et al., 2015), is widely used to calculate ESV. In this paper, basin ecosystem service is calculated based on ESV by the value equivalent method, whose results are used as the quantitative basis for determining the ecological source. The research method is as follows.

Firstly, calculate standard unit value equivalents, which is defined as a standard unit value equivalent to the economic value of the average natural grain yield per hectare of farmland per year (Xie et al., 2015). Most studies take rice, wheat, and corn as crops to calculate. Considering that the actual crops of Taihu are mainly grain, oil, and cotton, this paper uses the actual main crops to calculate the standard unit value equivalent, according to Equation 1.

$$P=N+L+M$$

Equation 1

In the equation: *P* represents the standard unit ecosystem service value. *N* represents the unit ecosystem service value of food crops per hectare. *L* represents the unit ecosystem service value of oil crops per hectare. *M* represents the unit ecosystem service value of cotton crops per hectare.

Then, equivalent values of ES are revised by combining with the actual situation of Taihu. According to the formula proposed by Xu (Xu et al.2012), the revision coefficient for Taihu is 0.73. According to Equation 2, calculate the equivalent value of ecosystem services of land use types for Taihu(Table 1).

$$C = 0.73 * C_r$$

Equation 2

In the equation: *C* represents the equivalent value of ES of land use types for Taihu. C_r represents the reference value of ES of land use types.

Table 1. The revised equivalent value of ecosystem services of land use types. Source: author owner-drawing.

Land use type	The types of ecosystem services										
	Supply service			Regulatory service				Support functions			Cultural function
	food supply	material supply	water supply	gas regulatory	climate regulatory	hydrological regulatory	environment purification	Soil conservation	Material circulation	Biodiversity	aesthetic landscape
waterbody	0.584	0.168	6.052	0.562	1.672	74.635	4.052	0.679	0.051	1.862	1.380
forestland	0.226	0.518	0.270	1.716	5.132	2.562	1.453	2.088	0.161	1.898	0.832
cropland	0.993	0.066	-1.920	0.810	0.416	1.986	0.124	0.007	0.139	0.153	0.066
grassland	0.277	0.409	0.226	1.438	3.803	2.789	1.256	1.752	0.131	1.591	0.701
wetlands	0.372	0.365	1.891	1.387	2.628	17.688	2.628	1.686	0.131	5.745	3.453
construction land	0.007	0.000	-5.482	-1.767	0.000	0.000	-1.796	0.015	0.000	0.248	0.007

Finally, calculate the values of eleven ecosystem services of each land use type, and summarize them to obtain the total ecosystem service value. The formula is as follows:

$$ESV = \sum_i (P \times C_{i,f} \times S_i)$$

Equation 3

In the equation: *ESV* represents the total value of ecosystem services. *C* represents the equivalent value of ecosystem services. *S* represents the area of the land use type. *i* represents the land use type. *f* represents the type of ecosystem services.

With the analysis of the above equations and GIS tools, the spatial differentiation characteristics of ESV can be illustrated. The area with positive value is regarded as the main supply area of ecosystem services. Previous studies subjectively screened the range of ecological sources (Li et al.,2019; Liu et al.,2019; Tan and Yao,2015). While in this study, the area with high value is selected as the important ecological source area. According to the analysis, combined with the quantitative characteristics of the ecological area (selecting the average value to represent the data characteristics of this group (Fan,1999), the ecological area with an area of more than 20 hectares is selected as important ecological sources.

3.3. Analysis method of ecological corridor based on circuit theory

The minimum cumulative resistance (MCR) is often used to analyse ecological corridors according to regional physical geographical conditions (Yan et al.,2021). This analysis method tends to ignore the attribute of free migration of organisms, while circuit theory makes up for the deficiency of the above method in cognition of biological movement in landscape ecology.

Circuit theory is to simulate the free migration process of organisms by using the random walk characteristics of current. The landscape matrix is regarded as a resistance surface, and resistance values are assigned to different landscape types to quantitatively simulate the path selection of free movement of organisms (Peng et al., 2018). The accumulated current on the landscape matrix represents the possibility of choosing the migration path of organisms, to judge the ecological corridor and its importance level.

The construction of ecological resistance surface is the analysis basis of circuit theory. Ecological resistance refers to the degree of difficulty for species to flow between different types of landscape units. Studies have shown that land use type is the main factor of ecological resistance (Yin et al.,2011). In this paper, the values of ecological resistance for Taihu are calculated by the reference value of existing studies (Yin et al.,2011; Kong et al.,2008) and the revision coefficient. Establish the revision index system by patch landscape index and ecosystem service value (Bu et al.,2005; Zhang et al.,2014), and use the entropy weight method (Zhu and Wei,2015) to calculate the revision coefficient. The formula of ecological resistance values for Taihu is as follows:

$$Z = \lambda * Z_e$$

Equation 4

In the equation: Z represents the ecological resistance values of different land use types in Taihu. λ represents the revision coefficient of ecological resistance value. Z_e represents the reference value of ecological resistance value of different land use types.

Based on the ecological resistance values, construct the ecological resistance surface, and use the circuit theory tools to quantitatively analyse the important ecological corridors and ecological restoration areas of corridors.

3.4. Analysis methods of water ecological pattern

Maintaining water security patterns plays an important role in constructing basin ecological infrastructure. In this paper, the water ecological pattern is constructed from three aspects: water ecosystem service value, water resources protection, and hydrological regulation (Yu et al.,2019). The analysis method of water ecosystem service value is the same as that in Section 3.2. Water source protection is to delimit the protected area according to the buffer zone. Hydrological regulation mainly analyzes the relationship between stormwater production and infiltration to delineate the inundation range of the basin, according to the SCS model (Table 2). Based on the analysis results of the above three aspects, the basin water ecological pattern was constructed.

Table 2. Analysis formula of the SCS model. Source: author owner-drawing.

analysis contents	analysis models	parameter meaning
Average runoff coefficient	$\overline{CN} = \sum\left(\frac{A_i}{A} * CN_i\right)$	In the equation: $\overline{CN}$ represents the average runoff coefficient. I represents the land of the same nature. A_i represents the total area of a certain type of land. A represents the total land area. CN_i represents the runoff coefficient of a certain type of land.
Rainwater retention	$S = \frac{25400}{CN} - 254$	In the equation: S represents the maximum possible rainwater retention. CN represents the surface runoff coefficient.
Rainwater runoff rate	$\begin{cases} Q = \frac{(P-0.2S)^2}{P+0.8S}, & P \geq 0.2S \\ Q = 0, & P < 0.2S \end{cases}$	In the equation: Q represents the rainwater runoff rate. P represents rainfall. S represents maximum possible rainwater retention.

4. Results

4.1. Holistic identification of ecological sources

80 ecological source patches were identified by GIS to extract ecological patches with an area of more than 20 hectares, whose total area accounts for 55.73% of the county. 19 patches are more than 100 hectares in area, and the remaining areas range from 20 to 97 hectares. The ecological sources with a large area in Taihu are distributed in the northwest of the county, while the ecological sources with a small area in the southeast, are mainly distributed in the towns of Xincang, Jiangtang, Chengxi, Jinxi, et al. (Figure 3).

4.2. Holistic identification of ecological corridors

Using the circuit theory tools, 132 ecological corridors were extracted. The total length is about 256.82km, among which the minimum length of the corridor is about 0.042km and the maximum length is about 14.59km. Ecological corridors are mainly distributed in the southeast of the county, with fewer and shorter ones in the northwest.

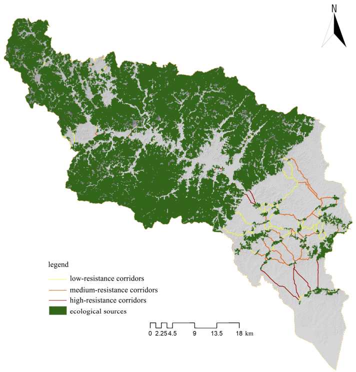
The ratio between cost-weighted distance and corridor length can reflect the relationship between ecological spatial resistance and the corridor (Pan and Wang,2021). A small ratio indicates that the resistance value of the ecological corridor is small. The analysis showed that the minimum value of this ratio in Taihu is 3.02, and the maximum value is 105.86. The analysis results were divided into three levels: high, middle, and low, including 67 low-resistance corridors and 46 medium-resistance corridors, which are mainly distributed in the central area of the county. There are 19 high-resistance corridors, mainly distributed in Xuqiao and Jinxi (Figure 3).

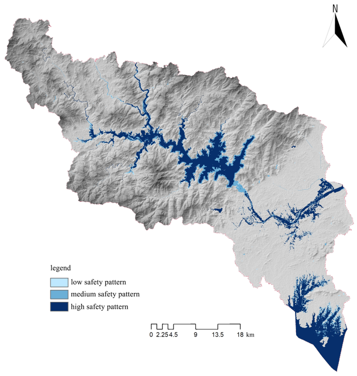
4.3. Holistic identification of water ecological pattern

The total area of water ecological pattern in Taihu is about 29709.65 hectares, accounting for 14.56% of the county area. The ecological pattern is divided into three safety levels, among which the area of low safety pattern is about 3911.91 hectares, the area of medium safety pattern is about 5586.14 hectares, and the area of high safety pattern is about 20211.60 hectares. The spatial distribution shows typical characteristics, in which the upper and lower reaches of the basin form two centers of water ecological pattern, including the surrounding towns radiating from Huating Lake and Bohu Lake (Figure 4).

4.4. Holistic identification of basin ecological infrastructure

The basin ecological infrastructure of Taihu is constructed based on land and water ecological patterns. The total area of basin ecological infrastructure in Taihu is about 159638.34 hectares, accounting for 78.25% of the county area. In terms of spatial distribution (Figure 5), the northwest region of the county has a good ecological security pattern, forming an ecological spatial structure with forest and water, which is an important ecological security barrier of Taihu. In the southeast, the water ecological pattern is mainly formed, which is small in scale and fragmented in distribution. In general, forests and basins are the main elements of the ecological pattern in Taihu. The characteristics of the ecological infrastructure pattern are strong in the northwest region and weak in the southeast region.





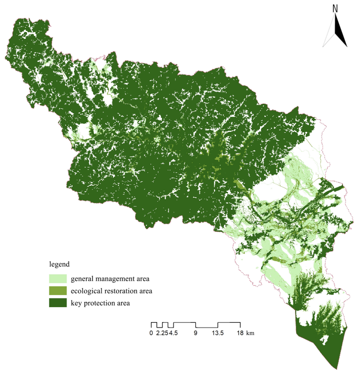


Figure 3. Ecological source areas and corridors of Taihu. Source: author owner-drawing.

Figure 4. Water ecological pattern of Taihu. Source: author owner-drawing.

Figure 5. The basin ecological infrastructure pattern of Taihu. Source: author owner-drawing.

5. Optimization strategies

The optimization of ecological patterns highlights the protection of important components of regional ecological structure and the improvement of ecological spatial structure. The appropriate management measures are proposed according to the differences in regional ecological services.

The key protected area is the basis for ensuring the overall security of ecological security patterns and has an important impact on ecological structure and function. The total area of key protected areas in Taihu is about 65% of the county area with forest and water as the mainland types, mainly distributed in the northwest towns of the county. In the management of key protected areas: give top priority to ecological protection, implement strict ecological conservation measures, improve the quality and efficiency of forestland and waters, and strictly monitor the damage caused by large-scale human activities. Key protected areas are the core areas of ecological infrastructure in land planning, which can serve as a primary basis for delineating ecological red lines.

The ecological restoration area plays an important role in effectively improving the function of the comprehensive ecological pattern. The regional ecological pattern can be effectively improved by enhancing the connectivity of ecological nodes and corridors. The general management area has a certain impact on the ecological pattern and can be used as a buffer for ecological protection. The area of ecological restoration area in Taihu accounts for about 3.33% of the county area and the general management is about 9.93% of the county area, which are mainly distributed in Xincang, Jiangtang, Xuqiao, Xiaochi, Chengxi, and Jinxi towns. In the ecological restoration area, implement ecological restoration projects, and guide the construction of ecological projects, including regional ecological infrastructure construction, ecological industry development, and ecological restoration. Ecological restoration areas can be included in the scope of territorial ecological protection planning. In the general management area, ecological industry development is encouraged to prevent excessive construction activities.

6. Discussion and conclusion

Ecosystem services value can quantitatively evaluate the ecological source and make up for the subjective judgment of previous study methods. The combination of ecosystem service value and circuit theory model can quantitatively analyze the spatial characteristics of basin ecological infrastructure and holistically identify basin ecological infrastructure, especially the ecological space with small ecological patches but high values. However, quantitative analysis results need to be combined with qualitative thinking judgment, because ecological planning involves complex mankind-land relationships. Quantitative tools can provide a reference for quantitative planning indicators, and help rationally make ecological planning.

The analysis of ecosystem services value is a quantitative research perspective. When using data for quantitative evaluation, pay attention to the difference between universal standard data and actual data, and make the research data closer to the actual situation. It is found that the traditional methods of ecological pattern construction tend to ignore water ecological elements, and the basin ecological infrastructure constructed by this method is incomplete. Therefore, the study of basin ecological infrastructure needs to add the analysis of water ecological patterns.

The quantitative analysis framework proposed in this paper can effectively identify basin ecological infrastructure. In the case of analysis, the framework has a better effect on analyzing the geospatial differences of basin ecological infrastructure, and this paper puts planning strategies according to the differences. The framework can be effectively combined with planning, and the quantitative results can be conveniently used for planning. The quantitative analysis framework can provide a process analysis method for eco-spatial planning.

7. References

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