

Changes in the Gross Ecosystem Product of Water Landscape Ecosystem Services in Zhaoqing City, China

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Abstract The ecosystem services of water landscapes offer significant benefits for human health, well-being, and socio-economic development. Utilizing data from 2013 to 2023, this study examined the evolving characteristics and determinants of the value of these services in Zhaoqing City. Results indicated that the gross ecosystem product from water landscapes has generally increased over the study period, ranging between 110.322 billion CNY and 140.320 billion CNY. Climate regulation was the dominant service value throughout, varying from 56.890 billion CNY to 73.087 billion CNY. Notably, the value derived from food supply more than doubled, while cultural services showed an upward trend, whereas values from water supply, water quality purification, and flood regulation declined. Supporting services remained consistent, valued between 13.853 billion CNY and 13.867 billion CNY, with biodiversity conservation constituting over 99% of this category. In terms of composition, climate regulation represented the largest share (50.18%–56.70%), followed by flood regulation (11.19%–20.77%). Transportation services constituted the smallest fraction, less than 0.02%. Determinant analysis revealed a significant positive correlation between the value of water landscape ecosystem services and evaporation, and a notable negative correlation with water area. Over this decade, Zhaoqing City's water landscape ecosystem has contributed diverse and crucial ecological benefits to regional development.

Keywords Water landscape, Ecosystem services, Gross ecosystem product, Evolution trend, Zhaoqing City

DOI 10.16785/j.issn 1943-989x.2026.1-2.005

Ecosystem services provide significant benefits to human health, well-being, and socioeconomic development. They intrinsically enhance both urban and rural living environments, playing a pivotal role in regional sustainable development^[1-2]. The concept of ecosystem services was first introduced in the 1970s, highlighting services such as climate regulation, water cycles, and nutrient cycles^[3]. Between the 1980s and early 1990s, researches predominantly centered on evaluating the recreational value of rivers, utilizing various models to analyze annual recreational benefits, conduct valuations, and establish comprehensive assessment frameworks^[4-6]. The seminal publications on ecosystem services in 1997^[7,8] triggered an exponential surge of research and notably assessed the value of global aquatic landscapes (lakes, wetlands, rivers), identifying 17 distinct service types including climate regulation, material cycling, and food production. For an extended period following this, evaluations of ecosystem services primarily concentrated on categorizing service values (e.g., use value and non-use value) and on regulating, provisioning, and information services offered by ecosystems^[8-9]. In recent times, there has been a growing emphasis on the carbon sequestration capabilities of water landscape ecosystems, the broadening of assessment frameworks, and the exploration of driving

factors within the context of climate change^[10].

The initial assessment of China's terrestrial ecosystem service function and its eco-economic value, carried out in 1999, revealed substantial economic benefits. However, the discourse on water landscape ecosystems was primarily confined to wetlands^[2]. The terrestrial water landscape ecosystem was further categorized into 4 types—river, reservoir, lake, and wetland—and the aquatic ecosystem services were divided into direct and indirect use values^[11]. For example, a study on urban lake wetlands in Chongqing found that human disturbance and the area of lake wetland were the determinants of direct and indirect values, respectively^[13]. In another case, an analysis of data from Guangzhou between 2005 and 2010 showed that the total value of its water landscape ecosystem services accounted for 7.66%–14.54% of the city's GDP—much higher than the national average of 1%–4%^[14]. The total service value of Shenzhen's water landscape ecosystem was 86.451 billion CNY, and the gross ecosystem product was 58.396 billion CNY^[15]. The gross ecosystem product of Qinghai Lake from 2010 to 2020 showed an upward trend with fluctuations [(609.4–784.9) billion CNY], and the water conservation value increased by 76.1 billion CNY, which played an important role in maintaining the ecological security of the eastern Qinghai-Tibet Plateau^[16].

Zhaoqing City, which is home to more than 40 rivers with catchment areas larger than 100 km² each (including the Xijiang River, Suijiang River, and Hejiang River), has abundant water resources of high quality. As a crucial but fragile ecological barrier in the Pearl River Delta, the quantity and value of ecosystem services provided by Zhaoqing's water landscape have important implications for socioeconomic development along the Guangzhou–Foshan–Zhaoqing metropolitan corridor and throughout the Pearl River Delta. Although it serves as an ecological shield for the Greater Bay Area, most studies on Zhaoqing have focused only on the degradation phase of Xiannv Lake, an urban lake^[17]. Therefore, this study evaluated the current service quantities and values of ecosystem services provided by Zhaoqing's water resources to clarify their role in regional sustainable development.

1 Materials and methods

1.1 Study area

Zhaoqing City, situated in the central-western region of Guangdong Province along the middle and lower reaches of the Xijiang River, is characterized by its unique geographical location. In 2020, it recorded an average annual precipitation of 1,491 mm, with surface water resources amounting to 127.12×10⁸ m³ and total

water resources at $127.40 \times 10^8 \text{ m}^3$. The per capita water resources in Zhaoqing stand at $3,357.5 \text{ m}^3$, significantly surpassing the national average of $2,100 \text{ m}^3$. Given its proximity to the Greater Bay Area, Zhaoqing not only acts as a crucial ecological barrier for the Pearl River Delta but also represents a sensitive area concerning the water environment. The city's water resource utilization is intricately linked to the socio-economic development of the Guangzhou-Foshan-Zhaoqing metropolitan area and extends its influence to the broader Pearl River Delta region.

1.2 Methods

Based on the analysis of water resource ecosystem service functions in Zhaoqing City from 2013 to 2023 and adhering to the principles of typicality of water landscape ecosystem services and spatial visualization of evaluation results, these services were categorized into 8 distinct groups. The detailed calculation methodologies are as follows:

(1) Water Supply: This encompasses the provision of industrial, domestic, agricultural, and ecological environment water replenishment by Zhaoqing City's water landscape ecosystem. Calculations employed the market value method^[13].

(2) Food Supply: Determined using the total fishery output values from the Zhaoqing Statistical Yearbooks spanning 2013–2023.

(3) Transportation Services: Valued based on data pertaining to water transportation service outputs from the aforementioned yearbooks.

(4) Water Quality Purification: Recognizing the ecosystem's pollutant assimilation capacity, the purification of chemical oxygen demand and ammonia nitrogen emissions from various wastewater sources was accounted for. This purification occurs through physicochemical processes like dilution, adsorption, filtration, and oxidation-reduction within the aquatic system. The market value method facilitated this calculation^[13].

(5) Climate Regulation: Significant due to heat absorption and evaporation from water surfaces, the functional value for climate regulation was ascertained using the substitute engineering method^[14].

(6) Flood Regulation and Storage: Leveraging the reservoir storage capacity of Zhaoqing City, this service's value was computed using the substitute engineering method^[15].

(7) Supporting services: These include air purification, carbon fixation and oxygen release, nutrient cycling, and species conservation. In

this study, the substitute engineering method was used to quantify the air purification capacity and the function of carbon fixation and oxygen release in Zhaoqing's water landscape ecosystem^[13–16]. The replacement cost method was applied to evaluate nutrient cycling^[16], while the value of species conservation was based on the willingness-to-pay for protected flora and fauna species and their respective populations.

(8) Cultural services: In addition to the above supporting, regulating, and supplying functions, the water landscape ecosystem also provides an important cultural service function, that is, providing high-quality recreational space for residents. In this study, the willingness-to-pay method was used to calculate the recreational value of the water landscape and the travel expenses paid voluntarily by people^[16].

The data employed in this study primarily encompass hydrological characteristics, environmental and climatic factors, as well as socio-economic indicators. These were sourced from the *Zhaoqing Statistical Yearbooks* (2013–2023) and the *Zhaoqing Water Resources Bulletins* (2013–2023). The figures presented herein were created utilizing Origin software.

2 Results

2.1 Changes in the gross ecosystem product of Zhaoqing City's water landscape ecosystems over the past decade

This study analyzed the ecosystem service functions of water landscapes in Zhaoqing City from 2013 to 2023 (Fig.1a). During this period, the total value of water landscape ecosystem services showed a significant upward trend, ranging from $(1,103.22 \times 10^8 \text{ CNY})$ to $(1,403.20 \times 10^8 \text{ CNY})$. The composition of water landscape ecosystem service values exhibited the following characteristics:

The value of water supply varied from 26.20×10^8 to $31.98 \times 10^8 \text{ CNY}$ with a downward trend overall (Fig.1b). Among its components, the values of agricultural water were between 18.61×10^8 and $22.46 \times 10^8 \text{ CNY}$, industrial water ranged from 2.61×10^8 to $5.66 \times 10^8 \text{ CNY}$, and domestic water was between 3.55×10^8 and $4.41 \times 10^8 \text{ CNY}$. Although the value of ecological environment water replenishment increased from 0.16×10^8 to $0.68 \times 10^8 \text{ CNY}$, it has shown an obvious increase in the last 3 years. The value of water purification services ranged from 20.91×10^8 to $50.84 \times 10^8 \text{ CNY}$ (Fig.1c). The value of climate regulation fluctuated between

568.9×10^8 and $730.87 \times 10^8 \text{ CNY}$ (Fig.1d). Specifically, the function of climate regulation mainly consisted of 2 processes: heat absorption by surface evaporation and air humidity enhancement. Among them, the value of heat absorption by surface evaporation ranged from 415.52×10^8 to $571.87 \times 10^8 \text{ CNY}$, while that of air humidity enhancement ranged from 144.32×10^8 to $159.22 \times 10^8 \text{ CNY}$.

Supporting services ranged from 138.53×10^8 to $138.67 \times 10^8 \text{ CNY}$ (Fig.1e), with the values in descending order: biodiversity conservation (138.23×10^8 – $138.41 \times 10^8 \text{ CNY}$) > oxygen release (0.14×10^8 – $0.17 \times 10^8 \text{ CNY}$) > nutrient cycling (0.05×10^8 – $0.06 \times 10^8 \text{ CNY}$) > carbon fixation (0.03×10^8 – $0.04 \times 10^8 \text{ CNY}$) > air purification. Cultural services (60.89×10^8 to $187.90 \times 10^8 \text{ CNY}$) showed an increasing trend (Fig.1f).

The steady and continuous growth of freshwater aquatic product output in Zhaoqing City drove the value of aquatic product supply to increase significantly, from $40.0 \times 10^8 \text{ CNY}$ in 2013 to $99.0 \times 10^8 \text{ CNY}$ in 2023 (Fig.1g). The value of flood regulation and storage varied between 136.11×10^8 – $234.91 \times 10^8 \text{ CNY}$, with a fluctuating downward trend (Fig.1h). Transportation services showed a fluctuating upward trend, ranging from 0.11×10^8 – $0.33 \times 10^8 \text{ CNY}$ (Fig.1i).

2.2 Proportional contribution and determinants of water landscape ecosystem services in Zhaoqing City

Over the past decade, the proportions of various water landscape ecosystem services in Zhaoqing City have changed differently. Among them, climate regulation, supporting services, cultural services, food supply and transportation services increased steadily, while water supply, water quality purification and flood regulation decreased (Fig.2a). In terms of the economic value of each service, the order was as follows: climate regulation (50.18%–56.70%) > flood regulation (11.19%–20.77%) > cultural services (6.09%–13.39%) > supporting services (9.88%–12.56%) > food supply (3.54%–7.10%) > water quality purification (1.59%–4.49%) > water supply (1.95%–2.83%) > transportation services (0.01%–0.02%). Climate regulation accounted for as high as 50.18% to 56.70%, which fully demonstrated that its value is irreplaceable and critical in the value of water landscape ecological services in Zhaoqing. With the gradual control and reduction of local industrial wastewater discharge, the value of water purification function in Zhaoqing also showed a downward

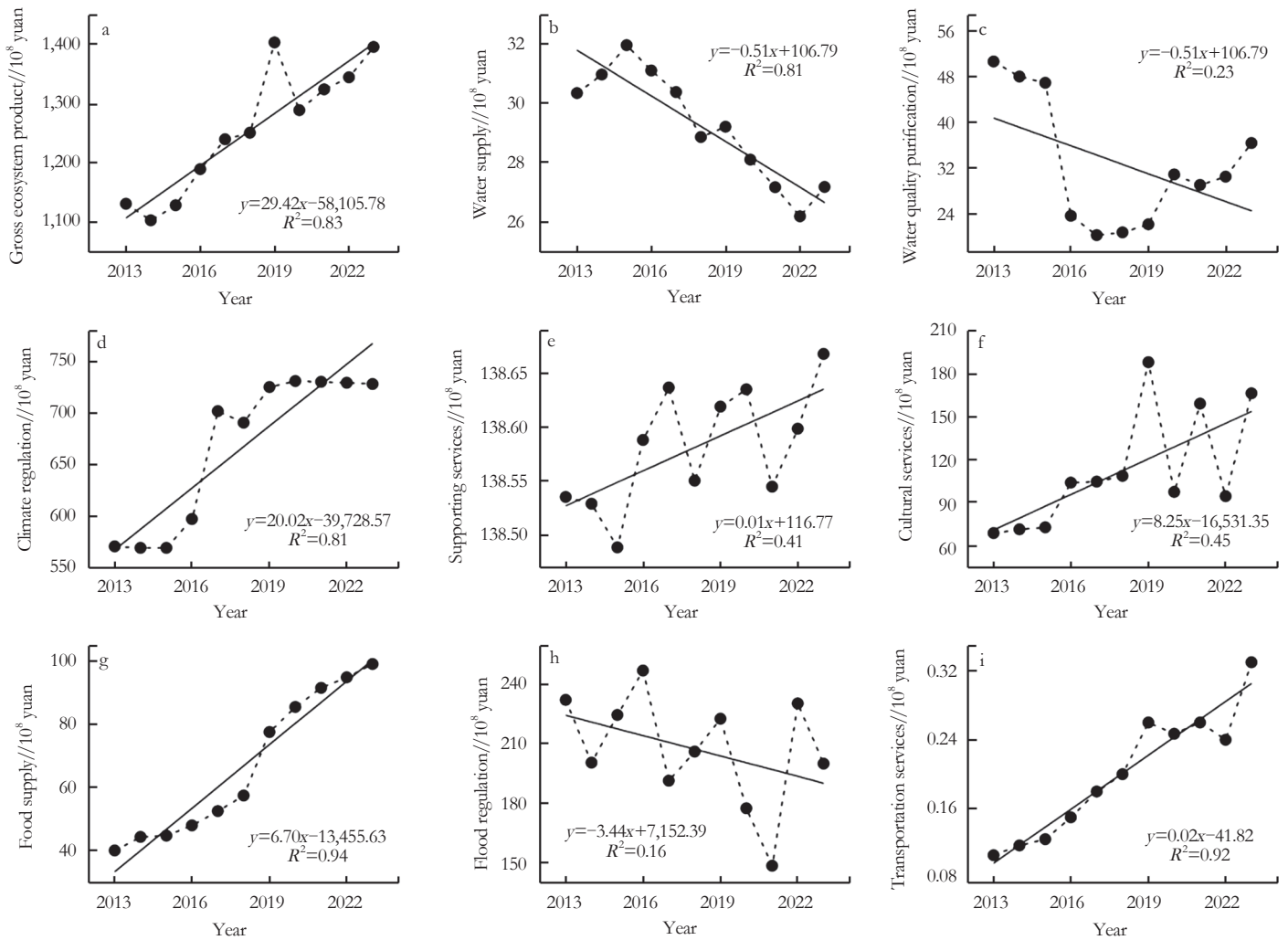


Fig.1 Changes in gross water ecosystem product and the value of each ecosystem service in Zhaoqing city from 2013 to 2023

trend as a whole, reflecting the direct impact of human activities on the water landscape ecosystem services. However, the proportion of transportation services has always been less than 0.02%. The value of biodiversity conservation accounted for the highest proportion of supporting services value (more than 99%), while the values of carbon fixation, oxygen release, and nutrient cycling accounted for relatively low proportions. Correlation analysis between the value of water landscape ecosystem services and climatic factors (temperature, precipitation, sunshine duration, evaporation) and water area in Zhaoqing City showed that it was significantly positively correlated with evaporation and negatively correlated with water area (Fig.2b).

3 Discussion

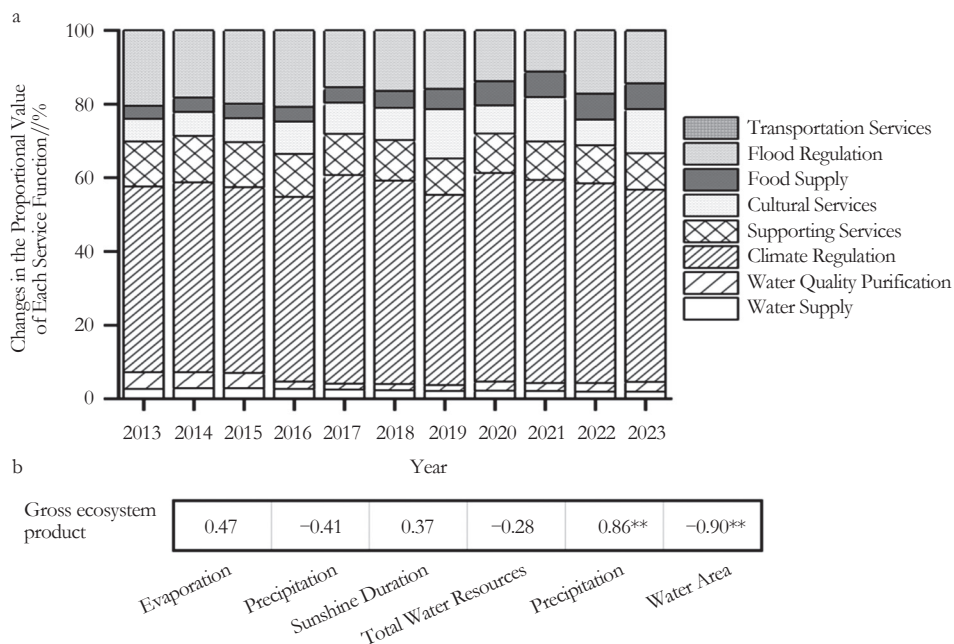
The total gross ecosystem product of the water landscape ecosystem in Zhaoqing City was higher than that in Guangzhou [(699.62–879.07) $\times 10^8$ CNY, 2005–2010] and Shenzhen

(864.51 $\times 10^8$ CNY, 2013), but lower than that in the Taihu Lake (3,528.73 $\times 10^8$ CNY) and the Qinghai Lake [(6,903.47–7,848.55) $\times 10^8$ CNY, 2010–2020]^[14–16]. The order of ecosystem service values for the water landscapes in Zhaoqing was as follows: climate regulation > flood regulation and storage > cultural services > supporting services > food supply > water purification > water supply > transportation services, which differed from the trends observed in Shenzhen and Guangzhou^[14–15]. However, the significant differences among the above results may be partially attributed to the variations in calculation methods, valuation criteria, timeframes, and ecological boundary definitions adopted by different studies when assessing the ecological service functions of aquatic landscapes.

Among the provisioning services of the Zhaoqing water landscape ecosystem, climate regulation had the highest value (50.18%–

18.14%–28.83%)^[15–16]. The water area of Zhaoqing City is 973.28 km², accounting for 6.53% of the city's total area, which plays an extremely important role in regional climate regulation. In addition, flood regulation services (accounting for 11.19%–20.77%) occupy an important position in the ecosystem service value of the Zhaoqing water landscape, effectively slowing down the flow rate, reducing the peak flood intensity, and balancing the distribution of floods, thereby reducing economic losses caused by flood disasters^[11]. At the same time, surface water storage capacity is also an important indicator to evaluate regional water resources conditions^[11].

The cultural services of Zhaoqing's water landscape ecosystem showed an increasing trend, although the tourism income decreased sharply in 2020–2022 due to special circumstances. Notably, the value of tourism services rebounded significantly in 2023, reaching 166.23 $\times 10^8$ CNY, which demonstrated that the tourism



Note: ** indicate statistical significance.

Fig.2 Proportional composition of water landscape ecosystem services in Zhaoqing City over the past decade (a) and influencing factors (b)

service within the cultural function of the water landscape had high resilience and recovery capacity^[14-15]. The supporting service value of Zhaoqing’s water landscape ecosystem ranged from 138.53×10^8 to 138.67×10^8 CNY, with biodiversity conservation being its most important component. As a key link in the ecological network, the health of this system was crucial for maintaining ecological balance^[2]. The values of carbon fixation, oxygen release, and nutrient cycling were relatively low, mainly because the productivity of phytoplankton in the water body was low. As the main biological group responsible for carbon fixation, oxygen release, and nutrient cycling in water bodies, the level of phytoplankton productivity directly limited the scale and intensity of these ecological processes, thereby affecting the corresponding service value^[16].

Capitalizing on its plentiful water resources, Zhaoqing City has consistently increased its freshwater aquatic product output, rising from 40.0×10^8 CNY in 2013 to an estimated 99.0×10^8 CNY in 2023. Three specific districts/cities—Gaoyao District, Sihui City, and Dinghu District—contain relatively large bodies of water, constituting approximately 67.90% of the city’s total water area. These regions offer abundant habitats for aquatic organisms, support crucial fishery resources, and yield significant quantities of aquatic products. This is also vitally important for preserving the food chain and ecological

equilibrium within the region.

4 Conclusion

This study analyzed the ecosystem service values of water landscapes in Zhaoqing City from 2013 to 2023. The results showed that the gross ecosystem product of water landscapes exhibited an overall upward trend during the study period, increasing from $1,103.22 \times 10^8$ CNY to $1,395.81 \times 10^8$ CNY. The changing trends of various service values showed clear divergence: climate regulation, cultural services, food supply, and transportation services increased steadily, among which the value of food supply increased from 40.0×10^8 CNY to 99.0×10^8 CNY, with an increase of 147.5%. In contrast, water supply, water quality purification and flood regulation, and storage decreased, with water supply decreasing from 31.98×10^8 CNY to 26.20×10^8 CNY and water quality purification decreasing from 50.84×10^8 CNY to 36.54×10^8 CNY. In terms of value composition, climate regulation accounted for the highest proportion (50.18%–56.70%) and was consistently dominant, followed by flood regulation and storage (11.19%–20.77%) and cultural services (6.09%–13.39%), while transportation services accounted for less than 0.02%. Analysis of influencing factors revealed that the value of water landscape ecosystem services was significantly positively correlated with evaporation and negatively correlated with water area. Over the past decade, the

water landscape ecosystem of Zhaoqing City has provided diverse and important ecological benefits for regional development. Future ecosystem management should focus on regulating service maintenance, biodiversity protection, and sustainable utilization of various services. Meanwhile, it is necessary to establish an evaluation system based on long-term dynamic monitoring to provide continuous support for the scientific management of regional water landscape ecosystems.

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feasible cultural relic protection plans and schemes as soon as possible, and urgently carry out reconstruction or restoration protection work in the future. These unclassified cultural relics should be included in cultural relic protection units as soon as possible, so that historical and cultural heritage can be inherited and continued.

2.2.4 Analysis on the current situation of heritage resource protection. Among the 122 cultural heritage sites registered in the red cultural heritage corridor in the Jiangxi section of the red army's long march, in addition to their well preserved condition, 52 sites have formed a relatively good historical landscape pattern as a whole (Dongmen Ferry, Yunshi Mountain Revolutionary Site Group, Yudu Central Committee Branch, Central Government Office Site Group, etc.). There are 34 well protected and relatively intact historical sites (such as the Kaixingwei Battle Monument, the former site of the Shicheng Blockade Command, and the former site of the Red Fourth Army Command in front of the post). There are 28 places with general protection status, but intact local historical features (such as the former site of the Red Ninth Army's assembly and departure, the former site of the Chongxian Red 21st Division Headquarters, etc.). There are 8 other sites with poor protection status and serious historical damage (Lichuan Xunkou, Zifuqiao, Tuancun Battle Site, former site of Xiazhao Red Ninth Army Corps Rest, etc.).

From the above analysis, it can be concluded that the current status of cultural heritage protection is closely related to its level of protection. In terms of protection level, cultural heritage at low level (such as county-level or unclassified) is poorly protected, while provincial-level and some municipal-level and county-level cultural heritages are well protected, and the protection of cultural heritage at national level and some provincial level are the best.

3 Conclusions

By combining the spatiotemporal distri-

bution characteristics of heritage resources, the development foundation of heritage resources themselves, and the inherent requirements for constructing heritage corridors, a hierarchical structure model is constructed. It determines the evaluation index system for the red cultural heritage corridor resources in the Jiangxi section of the red army's long march, which includes 12 indicator factors from three aspects: the value characteristics of heritage resources, the development foundation of heritage resources, and the protection status of heritage resources. The analytic hierarchy process (AHP) is used to conduct a systematic evaluation of the 128 heritage resources obtained from the census. An evaluation index system is constructed, and the weights of each factor are determined. Combined with Delphi expert consultation, a comprehensive score is given. Finally, 122 heritage resources are determined to be included in the registry through qualitative analysis.

After a systematic analysis of the red cultural heritage resources in the corridor, it is found that adopting a protection strategy with hierarchical classification and orderly management has a significant effect on improving the effectiveness of cultural heritage protection work; cultural heritage that is older and carries rich historical information is particularly precious due to its unique historical value and scarcity. With the expansion of the scope of heritage resource protection, the protection work is also facing more complex challenges, and the difficulty of protection is showing a significant upward trend. It hopes that the research can promote the attention of people from all walks of life to the red cultural heritage and their contemporary understanding of the long march spirit. At the same time, it strives to use this as an opportunity to explore the protection and utilization of revolutionary cultural routes with Chinese characteristics.

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