Spatiotemporal Evolution of Ecological Quality in Alpine Freshwater Lake Nature Reserves in the Past 20 Years

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Abstract The Caohai Nature Reserve is one of the three major plateau freshwater lakes in China. Since the 1950s, human activities such as land reclamation and population relocation have greatly damaged Caohai. A rapid evaluation of the spatiotemporal evolution trend of the ecological quality of the Caohai Nature Reserve is significant for the maintenance and construction of the ecosystem in this area. The research is based on the Google Earth Engine (GEE) remote sensing cloud computing platform. Landsat TM/OLI images from May to October in five time periods: 2000 – 2002, 2004 – 2006, 2009 – 2011, 2014 – 2016, and 2019 – 2021 were obtained to reconstruct the optimal cloud image set by averaging the images in each time period. By constructing four ecological indicators: Greenness (NDVI), Wetness (Wet), Hotness (LST), and Dryness (NDBSI), and using Principal Component Analysis (PCA) method to obtain the Remote Sensing Ecological Index (RSEI) for the corresponding years, the spatiotemporal variation of ecological quality in the Caohai Nature Reserve over 20 years was analyzed. The results indicate: ① the mean value of *RSEI* increased from 0.460 in 2000 – 2002 to 0.772 in 2019 – 2021, a 67.83% increase, indicating a significant improvement in the ecological quality of the reserve over the 20 years; ② from the perspective of functional zoning of the Caohai Nature Reserve, the ecological quality of the core area showed a degrading trend, while the ecological quality of the buffer zone and experimental zone significantly improved; ③ with the implementation of ecological restoration projects, the ecological quality of the reserve gradually recovered and improved from 2014 to 2021. The trend of *RSEI* value changes is well correlated with human interventions, indicating that the PCA-based RSEI model can be effectively used for ecological quality assessment in lake areas.

Key words Ecological restoration; Ecological quality; Remote sensing ecological index; Google Earth Engine; Caohai Nature Reserve

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The health of ecosystems is of great importance for human survival and the sustainable development of countries around the world[1]. Today's ecosystems face more severe human interference and environmental changes than ever before, which has a significant impact on global climate change and the natural environment[2 – 3]. Establishing nature reserves plays an important role in maintaining ecological security worldwide, conserving biodiversity in ecosystems, and improving the environment. The designation of specific areas for the protection of nature and the maintenance of ecosystem service performance and cultural value is achieved through legal or other effective means[4]. Grass Lake belongs to the inland water area nature reserve in the category of ecosystem reserve[5]. It was approved by the People's Government of Guizhou Province in 1985 to establish a provincial-level nature reserve, and was upgraded to a national-level nature reserve by the State Council in 1992. The biodiversity of the protected area is rich, with unique climate resources, and approximately one-sixth of all birds in China visit Grass Lake each year[6]. However, with the rapid development of science and technology and the social economy, frequent human activities and population pressure continue to affect ecological environment changes, leading to increasingly severe environmental issues such as vegetation destruction, soil erosion, extreme heat, and biodiversity loss. To address the ongoing deterioration of the ecological environment, obtaining a rapid overview of ecological quality status is of great significance for the ecological protection and socio-economic development of Grass Lake Nature Reserve.

Remote sensing spatial information technology has been widely used in the field of ecological environment due to its advantages of rapid, real-time, and large-scale monitoring[7]. The diversity and complexity of ecosystems often make it difficult for a single ecological indicator to comprehensively and effectively assess the current state of the ecological environment[8]. In 2006, the Ministry of Environmental Protection of China proposed the Ecological Environment Index (EI), which has been widely used for monitoring and evaluating ecological quality[9]. However, the EI faces challenges such as difficulty in acquisition and long data update cycles, making it unable to monitor the ecological environment status in real-time and continuously[7]. The use of comprehensive indices, such as the Analytic Hierarchy Process and the Pressure – State – Response (PSR) model, to integrate multiple indicators often faces issues such as difficulty in determining weights and the

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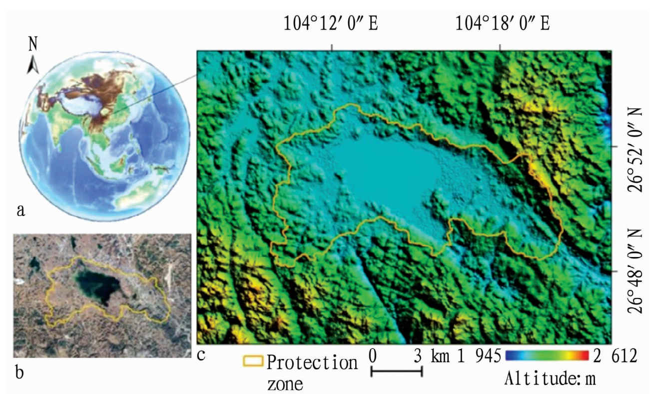
influence of human subjectivity[10-11]. In order to more objectively reflect changes in ecological quality, Xu H[12] proposed a new *RSEI* based on remote sensing information technology. This index integrates vegetation index, humidity component, land surface temperature, and built-up index, representing the four ecological elements of greenness, humidity, temperature, and dryness. Through principal component analysis, these four indices are coupled to obtain a comprehensive assessment index of ecological quality. The selected indicators are completely based on remote sensing information, making the acquisition process simple and the calculation process free from human subjectivity, resulting in strong objectivity and comparability of results. This new index has practical significance and high reference value for rapidly monitoring and evaluating regional ecological quality.

However, traditional methods for obtaining the *RSEI* face challenges such as cumbersome data collection and preprocessing, difficulties in cloud removal and image stitching, which limit the spatial and temporal application *of RSEI*[13]. By leveraging the vast remote sensing image data and geographical data stored in the Google Earth Engine (GEE), along with its high-performance computing capabilities, and utilizing the interactive development environment of the Web, online data usage and algorithm model construction can be realized, simplifying data processing and rapidly achieving cloud removal, image stitching, and index calculation. This addresses the legacy issues of traditional methods[14]. Currently, numerous scholars have widely applied the GEE platform in geoscience and environmental science[15] and for monitoring and evaluating ecological quality[7].

Based on the Landsat TM/OLI image dataset and surface water dataset integrated on the Google Earth Engine (GEE) platform, this study addresses the issue of obtaining high-frequency optical images due to the perennial cloudy and foggy weather in the study area. By using a three-year interval for mean fitting to construct cloud-free or nearly cloud-free images, the study calculates the ecological components of greenness, wetness, heat, and dryness. The *RSEI* for the Caohai National Nature Reserve in Guizhou is obtained using the principal component analysis method. The study analyzes the spatiotemporal evolution trend of ecological quality from 2000 to 2021, aiming to monitor and evaluate the ecological quality of the Caohai National Nature Reserve, and to provide a theoretical reference for the management decisions of the protected area.

1 Study area and data

1.1 Overview of the study area Caohai is located in the southwest of Weining Yi and Miao Autonomous County in Guizhou Province, China (26°47′–26°52′ N, 104°10′–104°20′ E). It is the largest plateau natural freshwater lake in Guizhou, a nationally important wetland in China (Class I), and one of the "world's best wetland bird-watching areas". The area covers 120 km^2, with an average water surface area of 25 km^2. The water area of Caohai Lake varies seasonally due to rainfall. Caohai belongs to the Yangtze River system, and the nature reserve is part of a complete and typical plateau wetland ecosystem with a unique plateau climate. The average temperature is 10.6 °C, the average annual rainfall is 950 mm, and the average relative humidity is 79%. There are no severe cold in winter or extreme heat in summer, with distinct wet and dry seasons. The wet season lasts from May to October, and the dry season is from November to April of the following year, characterized by low humidity, dry conditions, and large diurnal temperature differences[16-18]. The northern and eastern parts of the Caohai National Nature Reserve border the county town, while the southern and western parts are adjacent to more residential points and agricultural production areas, facing significant pressure from human production and living activities. Through the efforts of all parties, a series of effective measures such as pollution control and lake purification, converting farmland back to lake, relocating the city to restore the lake, and relocating villages to restore the lake have been taken, achieving significant results in the comprehensive management of the Caohai Nature Reserve. Illustration of the study area is shown as Fig. 1.



Note: a. Location of the study area in the world; b. Satellite image of the study area, with rural areas in the western and southern parts, and neighboring urban areas in the northern and eastern parts; c. Topographic rendering of the study area.

Fig. 1 Illustration of the study area

1.2 Data acquisition and preprocessing The Landsat remote sensing data originates from the United States Geological Survey (USGS) and is part of the integrated dataset on the Google Earth Engine (GEE) platform at [https://earthengine.google.com/platform/]. The study selected Landsat 5 and Landsat 8 Surface Reflectance (SR) data products, with both having a spatial resolution of 30 m and a temporal resolution of 16 d. The data has undergone geometric correction, radiometric calibration, and atmospheric correction[19]. Due to the climatic conditions in low-latitude regions, the cloud cover in the study area has a significant impact. Therefore, based on GEE programming (JavaScript), images with good quality and imaging times targeting the years of interest and one year before and after, from May to October, were screened. For the years 2000–2002 and 2004–2006, Landsat 5 (TM) data was selected, while for the years 2009–2011, 2014–2016, and 2019–2021, Landsat 8 (OLI) data was chosen. The cloud mask algorithm provided by the GEE platform was used to remove cloudcontaminated pixels and mean composite pixels were employed to obtain images with few or no clouds.

1.3 Calculating RSEI in Google Earth Engine The GEE platform is a PB-level geographic data science analysis platform jointly developed by Google, Carnegie Mellon University, and the United States Geological Survey, providing API interfaces based on JavaScript and Python languages. The use of a web-based interactive development environment enables processing, analysis, and visualization of cloud-based data[20]. The platform provides users with commonly used remote sensing datasets such as Landsat, MODIS, and Sentinel, as well as common geospatial datasets such as terrain, land cover, and surface temperature[15]. Based on the cloudy and foggy climate conditions in the study area, the Landsat cloud mask algorithm provided by the GEE platform is used to detect and remove cloud pixels and cloud shadows in image time series for the target year, and then fitting the mean values in cloud-free image areas to obtain the optimal Landsat image data for the study area[21].

Based on Xu H's proposal of remote sensing ecological indices for Landsat images[12], vegetation index, the wetness component of brightness transformation, land surface temperature, and dryness components (built-up index and bare soil index) are used as four indicators of remote sensing ecological indices. The remote sensing comprehensive ecological index is constructed using Principal Component Analysis (PCA) to avoid errors caused by human factors. Xu H uses an improved MNDWI water index to remove water information[22], and it can directly access the JRC Global Surface Water dataset integrated into the GEE platform. This dataset contains location and temporal distribution maps of surface water from 1984 to 2019 and provides statistical data on the extent and changes of these water bodies, simplifying the operation process and avoiding the impact of water information on the calculation of wetness components.

The *RSEI* can be expressed as a function of these four indicators:

$$RSEI = f(G, W, T, D) \quad (1)$$

Its remote sensing definition is:

$$RSEI = f(NDVI, Wet, LST, NDBSI) \quad (2)$$

In the formula, G represents greenness; W represents humidity; T represents temperature; D represents dryness; *NDVI* is the vegetation index; *Wet* is the humidity component; *LST* is the land surface temperature, and *NDBSI* is the building and bare soil index.

Before conducting principal component analysis, the platform GEE was utilized for programming to calculate and positively normalize each component indicator, unifying their scales to the range [0, 1]. The normalization formula for each indicator is:

$$MMS = (I - I_{min})/(I_{max} - I_{min}) \quad (3)$$

In the equation, *MMS* represents the normalized value of a certain indicator; I represents the values of four ecological component indicators; I_{max} is the maximum value of that indicator, and I_{min} is the minimum value of that indicator. Additionally, in order to avoid the impact of water bodies on the computation of humidity component, the surface water data set integrated in the GEE platform was called upon to mask the water information in the research area. Subsequently, after the 4 indicators were processed with normalization, a new composite image was created for principal component analysis. The first principal component *PC*1 was obtained. In order for larger values of *PC*1 to represent better ecological conditions, 1 − *PC*1 was used to obtain the initial ecological index $RSEI_0$[12]:

$$RSEI_0 = 1 - \{PC1[f(NDVI, Wet, LST, NDBSI)]\} \quad (4)$$

*PC*1 is the first principal component. Similarly, using equation (3) to normalize $RSEI_0$, the final *RSEI* is obtained, which is between [0, 1]. The closer the *RSEI* value is to 1, the better the ecological quality.

$$RSEI = (RSEI_0 - RSEI_{0\_min})/(RSEI_{0\_max} - RSEI_{0\_min}) \quad (5)$$

To further analyze the spatial distribution of ecological quality in the Caohai Nature Reserve, the *RSEI* was divided into 5 levels with equal intervals of 0.2 (Table 1)[12].

Table 1 *RSEI* equidistant classification

Level	*RSEI*	Level description
I	0 – 0.2	Worse
II	0.2 – 0.4	Poor
III	0.4 – 0.6	Moderate
IV	0.6 – 0.8	Good
V	0.8 – 1.0	Excellent

2 Results and analysis

2.1 Spatiotemporal changes in ecological quality From the principal component analysis results in Table 2, it can be seen that the characteristic vectors of the *NDVI* representing greenness and the *Wet* component representing humidity in the principal component *PC*1 are both positive, while the characteristic vectors of the *LST* representing temperature and the *NDBSI* representing dryness are both negative. This is consistent with the positive effects of greenness and humidity on the ecological environment, and the negative effects of dryness and temperature in actual ecosystems. During the period from 2000 to 2011, the temperature component was the main ecological influencing component, while during the period from 2014 to 2021, the greenness component was the main influencing component. Furthermore, compared to other principal components, the contribution rate of the characteristic values of *PC*1 in each period concentrates around 65% of the characteristic information of each indicator, indicating that using *PC*1 to create a *RSEI* is reasonable.

From Fig. 2, it can be observed that during the period from 2000 to 2006, the ecological quality within the reserve deteriorated significantly in the eastern region, improved slightly in the western region, and from 2006 to 2011, the ecological quality in the eastern region increased slightly while the quality in the western region declined. During the period from 2011 to 2020, the ecological quality around the lake area and the northern urban area within the reserve clearly deteriorated, while the quality improved significantly in other regions. The ecological quality in the main urban area adjacent to Caohai Lake showed a degradation trend from 2000 to 2016 and improved from 2019 to 2021.

Table 2 Principal component analysis results

Ecological indicators	2000 – 2002	2004 – 2006	2009 – 2011	2014 – 2016	2019 – 2021
NDVI	0.003 0	0.433 0	0.225 0	0.644 0	0.906 0
Wet	0.651 0	0.495 0	0.562 0	0.282 0	0.147 0
LST	−0.652 0	−0.598 0	−0.645 0	−0.604 0	−0.387 0
NDBSI	−0.389 0	−0.458 0	−0.467 0	−0.377 0	−0.089 0
Eigenvalue value	0.039 7	0.041 2	0.033 5	0.033 8	0.044 1
Eigenvalue contribution rate//%	65.350 0	74.250 0	68.620 0	73.340 0	64.400 0

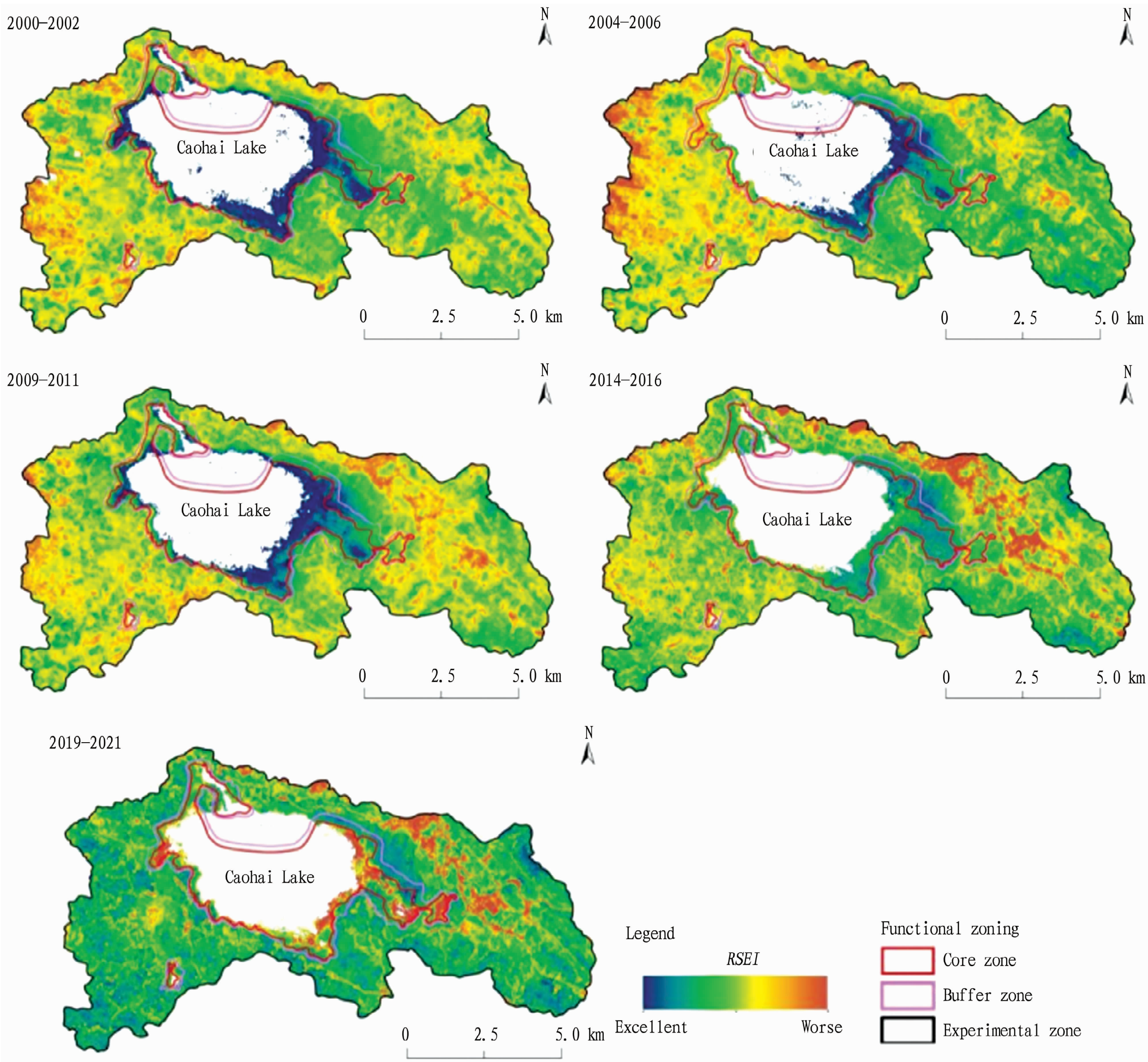


Fig. 2 Temporal and spatial evolution of interannual *RSEI* from 2000 to 2021

2.2 Interannual changes in ecological quality transition As illustrated in Fig. 3, the area of improved ecological quality between 2000 and 2006 was 23.99 km^2, accounting for 29.35% of the total study area, while the area of ecological quality degradation was 7.87 km^2, representing 9.63% of the total area, indicating an overall improvement in ecological quality during this period. From 2004 to 2011, the area with improved ecological quality was 8.73 km^2, accounting for 10.62% of the total area, and the area of degradation was 23.37 km^2, accounting for 28.45% of the total area. The area of ecological quality degradation was higher than the area of improvement, suggesting a decline in ecological quality during this period. Between 2009 and 2016, the area with improved ecological quality was 47.09 km^2, accounting for 57.21% of the total area, while the area of ecological quality degradation was 4.48 km^2, accounting for 5.45% of the total area. The area of improvement was greater than the area of degradation, indicating an overall improvement in ecological quality during this period. From 2014 to 2021, the area with improved ecological quality was 67.21 km^2, accounting for 82.58% the total area, and the area of ecological quality degradation was 4.47 km^2, accounting for 5.49% of the total area, showing a significant improvement in ecological quality during this period.

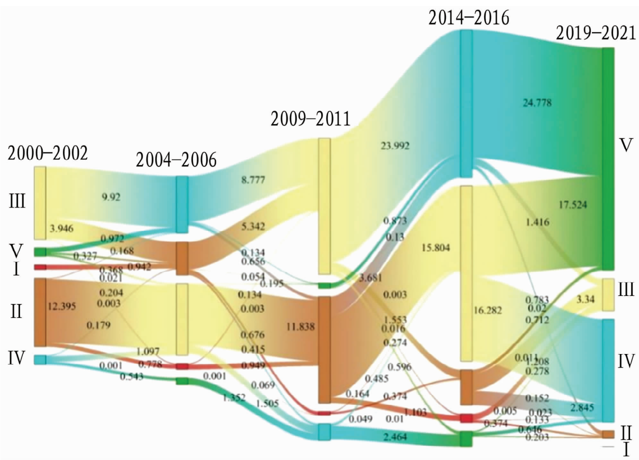


Fig. 3 Transition of different ecological quality levels from 2000 to 2021

2.3 Changes in ecological quality in different functional zones The Caohai Nature Reserve functional zones consist of a core zone, buffer zone, and experimental zone. In the core zone, all human activities are strictly prohibited. Access to the buffer zone is only allowed for scientific research and observation activities. The experimental zone is located around the buffer zone and allows for scientific experiments, teaching internships, excursions, tours, domestication, breeding of rare and endangered wildlife and plants, as well as limited production activities, some settlement points, and tourist facilities[23]. The core zone is concentrated with habitats and foraging grounds for rare and endangered waterfowl such as Caohai Lake, shallow water marshes, sedge wetlands, meadows, grasslands, *etc.* The buffer zone extends from 100 to 500 m outside the core zone, encompassing both water and land areas. The experimental zone is located beyond the buffer zone[18].

2.3.1 Changes in ecological quality in the core zone. The ecological quality grades from 2000 to 2021 were mainly concentrated between grades IV and V (0.6 to 1.0) in terms of the area they covered. Between 2000 and 2006, the area proportion in grades II to IV (0.2 to 0.8) increased by 5%, 11%, and 3% respectively, while the area in grade V decreased by 18%, leading to an overall decline in ecological quality by 31%. From 2006 to 2011, the proportion of area in grade IV rose by 17%, while the proportions in grades II, III, and V each fell by 5%, 9%, and 3% respectively, resulting in a 28% overall improvement in ecological quality compared to the previous period. Between 2011 and 2016, the proportion of area in grade IV increased by 14%, while the proportions in grades II, III, and V each decreased by 1%, 9%, and 4% respectively, with the ecological quality rising by 2% compared to the previous period. In the period from 2016 to 2021, the proportions of areas in grades I to III and V increased by 1%, 14%, 11%, and 7% respectively, while the proportion in grade IV decreased by 33%, leading to a 30% decline in ecological quality. In summary, the ecological quality in the core area of the Caohai Nature Reserve generally showed a downward trend from 2000 to 2006, improved from 2006 to 2016, and declined significantly from 2016 to 2021 (Fig. 4, Table 4).

2.3.2 Changes in ecological quality in the buffer zone. From 2000 to 2021, the distribution of ecological quality grades in the buffer zone was primarily concentrated between III and V (0.4 to 0.6) from 2000 to 2011, and predominantly between IV and V (0.6 to 1.0) from 2011 to 2021. Between 2000 and 2006, the area with grades IV to V increased by 9% and 1% respectively, while the area with grades II to III (0.2 to 0.6) decreased by 2% and 8% respectively, resulting in an overall improvement of 4% in ecological quality. From 2006 to 2011, the proportion of area with grade III increased by 9%, and grades IV to V decreased by 5% and 3% respectively, leading to a 1% overall increase in ecological quality. Between 2011 and 2016, the area with grades II and III decreased by 6% and 39% respectively, while the area with grades IV and V increased by 30% and 14% respectively, resulting in a 14% improvement in ecological quality. From 2016 to 2021, the area with grade II increased by 1%, while the areas with grades III and IV decreased by 15% and 40% respectively. The area with grade V increased by 54%, leading to a 2% decline in ecological quality. Overall, the ecological quality in the buffer zone of the Caohai Nature Reserve continued to improve from 2000 to 2016, experienced a slight decline from 2019 to 2021, and showed an overall improvement (Fig. 4, Table 5).

2.3.3 Changes in ecological quality in the experimental zone. Between 2000 and 2011, the area distribution of ecological quality grades mainly focused between II and III (0.2 to 0.6), from 2014 to 2016 primarily between III and IV (0.6 to 0.8), and from 2019 to 2021 mainly between IV and V (0.8 to 1.0). During the period from 2000 to 2006, the area with grades II and III decreased by 12% and 1% respectively, while the area with grade IV increased by 13%, leading to an overall 24% improvement in ecological quality, mainly concentrated in the western region. Between 2006 and 2011, the proportion of area with grades I and IV decreased by 1% and 11% respectively, while the area with grades II to III increased by 10% and 1% respectively, resulting in a 19% overall decline in ecological quality, mainly due to the decline in ecological quality in the western region. From 2011 to 2016, the area with grades II and III decreased by 26% and 10% respectively, while the area with grades I, IV, and V increased by 1%, 33%, and 2% respectively, leading to a significant 50% improvement in ecological quality, with improvements in the ecological quality around the eastern region and western town areas. Between 2016 and 2021, the area proportions of grades I to IV decreased by 2%, 9%, 40%, and 4% respectively, while the area of grade V increased by 56%, resulting in an overall 23% improvement in ecological quality, with significant improvements in the ecological quality around the eastern region and western town areas. Overall, the ecological quality in the experimental zone of the Caohai Nature Reserve showed an overall improvement from 2000 to 2006, followed by a decline from 2006 to 2011, and significant improvement from 2014 to 2021.

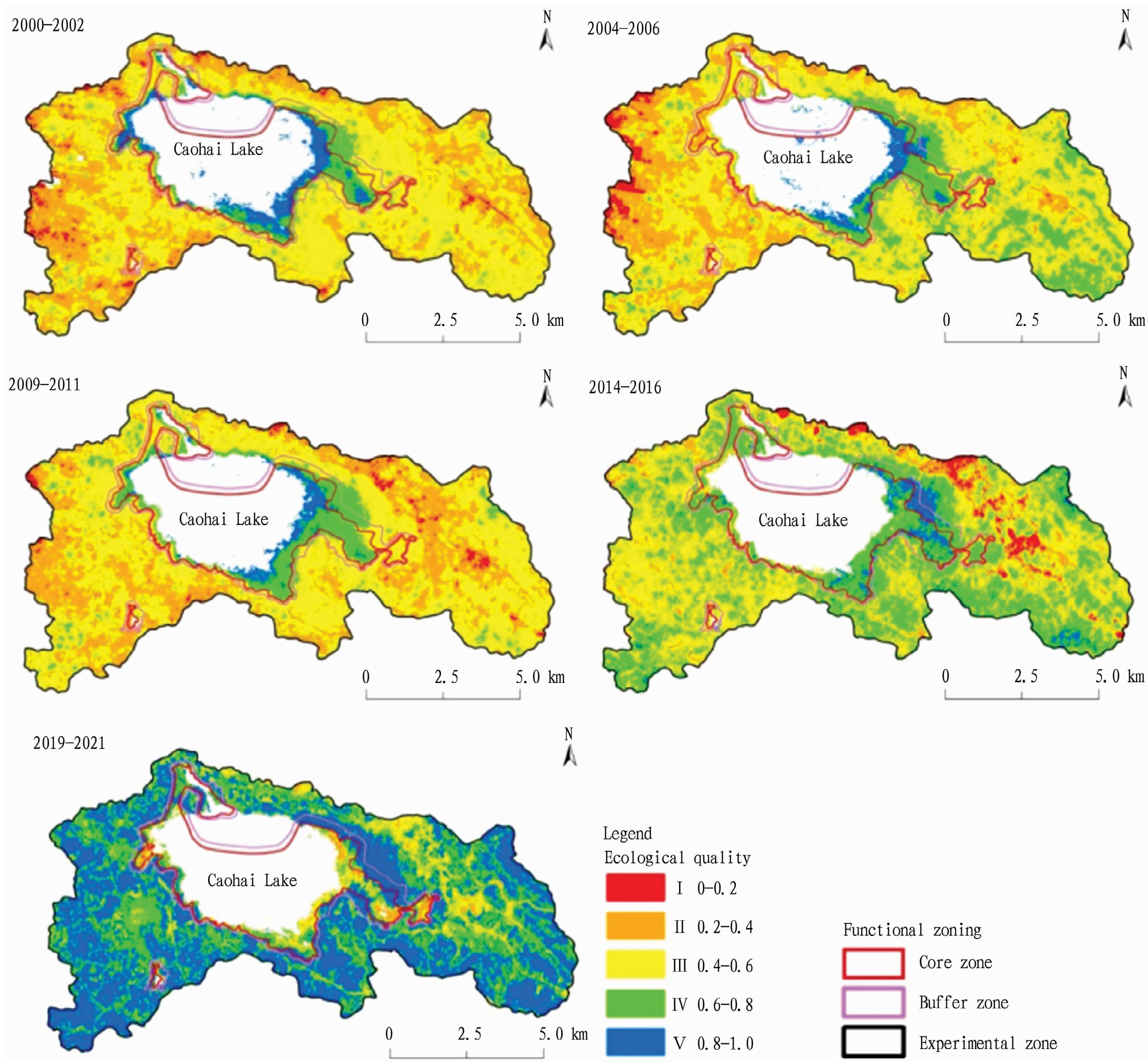


Fig. 4 Spatiotemporal changes in ecological quality across different functional zones

Table 4 Changes in *RSEI* grade in the core zone from 2000 to 2021

Ecological quality level	2000 – 2002		2004 – 2006		2009 – 2011		2014 – 2016		2019 – 2021	
	Area//km^2	Percentage//%	Area//km^2	Percentage//%	Area//km^2	Percentage//%	Area//km^2	Percentage//%	Area//km^2	Percentage//%
I	0	0	0	0	0	0	0	0	0.04	1
II	0.18	2	0.54	7	0.16	2	0.07	1	0.99	15
III	1.43	18	2.15	29	1.67	20	0.83	11	1.49	22
IV	2.67	34	2.77	37	4.61	54	5.24	68	2.33	35
V	3.68	46	2.07	28	2.09	25	1.58	21	1.88	28
Total	7.96	100	7.52	100	8.53	100	7.72	100	6.74	100

Table 5 Changes in *RSEI* grade in the buffer zone from 2000 to 2021

Ecological quality level	2000 – 2002		2004 – 2006		2009 – 2011		2014 – 2016		2019 – 2021	
	Area//km²	Percentage//%	Area//km²	Percentage//%	Area//km²	Percentage//%	Area//km²	Percentage//%	Area//km²	Percentage//%
I	0	0	0	0	0	0	0	0	0	0
II	0.43	9	0.32	7	0.31	7	0.03	1	0.07	2
III	2.69	57	2.31	49	2.74	58	0.90	19	0.20	4
IV	1.36	29	1.78	38	1.53	33	2.96	63	1.10	23
V	0.22	5	0.28	6	0.12	3	0.81	17	3.31	71
Total	4.69	100	4.69	100	4.71	100	4.70	100	4.68	100

Table 6 Changes in *RSEI* grade in the experimental zone from 2000 to 2021

Ecological quality level	2000 – 2002		2004 – 2006		2009 – 2011		2014 – 2016		2019 – 2021	
	Area//km²	Percentage//%	Area//km²	Percentage//%	Area//km²	Percentage//%	Area//km²	Percentage//%	Area//km²	Percentage//%
I	1.19	2	1.29	2	0.89	1	1.73	2	0	0
II	25.98	38	17.88	26	25.21	36	6.99	10	0.61	1
III	40.55	59	40.03	58	40.83	59	33.75	49	5.94	9
IV	1.38	2	10.07	15	2.47	4	25.85	37	22.81	33
V	0.13	0	0.14	0	0.07	0	1.17	2	40.08	58
Total	69.22	100	69.39	100	69.47	100	69.49	100	69.44	100

3 Discussion and conclusions

3.1 Discussion

(1) Through consulting related materials, from the pilot meeting on Lake Grass in the Grass Lake Nature Reserve in 2013, until the approval of the "Guizhou Caohai Plateau Karst Lakes Ecological Protection and Comprehensive Management Plan" by the National Development and Reform Commission in 2015, due to its evident ecological fragility and excessive human exploitation and use, the ecological quality of the Grass Lake Nature Reserve was severely affected. This corresponds to the findings in this study that the ecological quality level of the Grass Lake Nature Reserve was concentrated at a medium to lower level from 2000 to 2011. With the proposal of management plans and the implementation of measures, the ecological quality of the Grass Lake Nature Reserve gradually improved from 2014 to 2021, indirectly confirming the reference value of this study's results and the effectiveness of using principal component analysis to construct the *RSEI* model for regional ecological quality assessment.

(2) The ecological environment of the Grass Lake Nature Reserve is closely related to human societal activities. Its special location adjacent to Weining County poses a need to strengthen supervision and management of the ecological environment while vigorously developing the socio-economy. It is important to continuously monitor the spatial and temporal changes in the regional ecological quality, increase efforts in ecological environment protection, improve protection mechanisms and response measures, enhance public awareness of environmental protection, promote the unity of urban development and environmental harmony, achieve harmonious coexistence between humans and nature, and steadfastly pursue a strategy of sustainable development.

(3) The shallow water areas near the edges of the core zone of the Grass Lake Nature Reserve are perennially covered with floating vegetation, which has a significant impact on the ecological environmental quality during the breeding season[27–28]. Further research is needed to investigate whether the results and trends of the *RSEI* in the core zone are associated with this impact. The study did not consider the correlation between natural and human factors within the region and the remote sensing ecological indices. Additionally, using multi-year images from similar seasons as a substitute for single-year images to construct the *RSEI* may have a certain impact on the accuracy and comparability of ecological quality evaluation in the study area. Further research is needed to determine whether remote sensing ecological indices can accurately represent the ecological quality in different regions and whether there are better ecological indicators to represent the ecological situation.

3.2 Conclusions

(1) The contribution rates of the eigenvalues of the four ecological components of the *RSEI* were all around 65% in the first principal component (*PC*1), indicating that *PC*1 contains most of the characteristic information of the four ecological components. Additionally, the greenness and humidity components showed a positive correlation with ecological quality, while the temperature and dryness components exhibited a negative correlation. Therefore, it is reasonable to construct the *RSEI* using *PC*1.

(2) From 2000 to 2021, the overall ecological quality of the Caohai Nature Reserve showed an upward trend. The average *RSEI* value increased from 0.460 in 2000 – 2002 to 0.772 in 2019 – 2021. The ecological quality levels gradually improved from a moderate to lower level to mainly good levels, with the most significant improvement observed in the eastern part of the study area. Conversely, there was a slight degradation trend in the ecological quality of the main urban area in the western region.

(3) The ecological quality of the core zone of the Grass Lake

Nature Reserve remained at a good level with no significant trend from 2000 to 2011, but showed a slight decline from 2014 to 2021. The ecological quality in the buffer zone continuously improved from 2000 to 2016, experienced a slight decrease in 2019 to 2021, resulting in an overall improvement. In the experimental zone, the ecological quality increased from 2000 to 2006, then decreased from 2006 to 2011, and showed significant improvement from 2014 to 2021.

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