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Characterization of the Spatial and Temporal Evolution of Water Environment Quality in Yilong Lake

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Abstract To conduct a comprehensive analysis of the current status of water environment quality in Yilong Lake, a systematic study was undertaken to characterize the evolution of water quality. This study utilized monthly data on water quality indicators collected from three monitoring sections of Yilong Lake between 2016 and 2023, employing the Mann-Kendall trend test and ArcGIS spatial interpolation technique. The results indicated that the five-day biochemical oxygen demand (BOD_5), total nitrogen (TN), and chlorophyll a (Chla) exhibited an overall increasing trend, whereas other indicators demonstrated a decreasing trend. The permanganate index (PI), chemical oxygen demand (COD), TN, and Chla were observed in the following order: east of the lake > middle of the lake > west of the lake. In contrast, the BOD_5 and total phosphorus (TP) were ranked as west of the lake > east of the lake > middle of the lake. Additionally, ammonia nitrogen (NH_3-N) was found to be in the order of east of the lake > west of the lake > middle of the lake, while transparency was ranked as west of the lake > middle of the lake > east of the lake. Urban domestic sewage, effluent from industrial parks, domestic waste generated by rural residents' production and daily activities, agricultural waste, wastewater from decentralized farming, domestic sewage, and point source discharges from the soybean processing industry are the primary contributors to the exceedance of water quality standards. The enhancement of a precise pollution control system, along with the regulation of pollution sources and the interception of pollutants, can significantly diminish the pollution load entering the lake. This approach is essential for the protection and restoration of river and lake ecosystems, thereby facilitating the gradual recovery of their ecological functions. Additionally, the implementation of ecological water replenishment and the recycling of water resources can improve the capacity of the water environment. Furthermore, bolstering scientific and technological support, as well as comprehensive supervision and assurance measures, is crucial to ensuring that water quality remains stable and adheres to established standards.

Keywords Evolution characteristics of water environment quality, Mann-Kendall test, ArcGIS spatial interpolation, Yilong Lake

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Water is a vital resource for human survival, and lakes serve as crucial freshwater reservoirs and constitute a significant element of river ecosystems. They provide a range of ecological services, including the regulation of river runoff, flood control and storage, aquaculture, irrigation, water quality purification, tourism, climate regulation, and the preservation of biodiversity[1-2]. The growth of human populations in proximity to lakes, coupled with social and economic development and inadequate wastewater management, has intensified the demand for high-quality water sources. Consequently, the development and utilization of water resources have escalated[3]. This situation has resulted in numerous lakes facing challenges such as diminishing surface area, reduced water volume[4], declining water quality, impaired purification capacity[5], destruction of biological habitats, decreased biodiversity[6], and significant degradation of ecological functions within lake ecosystems[7].

The nine plateau lakes located in Yunnan Province constitute a significant component of the national ecological security barrier in southwest China. Yilong Lake, one of these nine plateau lakes, has contributed substantially to the social and economic development of the local region. In recent years, the intensity of human activities in the Yilong Lake basin has been increasing significantly. The challenge of reducing pollution loads is substantial, and when combined with the pressing issues of resource-based water scarcity and severe ecological degradation, it becomes increasingly difficult to enhance water quality. Currently, research on Yilong Lake predominantly centers on phytoplankton, algal communities[8], wetlands[9], water quality assessment, and landscape patterns[10]. Enhancing the analysis of dynamic changes in water quality will allow managers to more accurately predict trends in water quality changes at Yilong Lake. This, in turn, will facilitate the implementation of targeted scientific protection and management strategies in a timely manner.

1 Data and methods

1.1 Overview of the study area and data

Yilong Lake serves as the source of the Lujiang River, which is a tributary of the Nanpan River. It is classified as a fault erosion lake and exhibits a semi-closed flow state. The lake's planform extends in an east-west orientation, encompassing a basin area of approximately 1,300 km^2, with a normal storage level of 1,414.2 m. The Yilong Lake basin is primarily dominated by surface runoff, which constitutes 46%–53% of the total water catchment within the basin. Seven major rivers contribute to the inflow of water into the lake: the Chiruihai River (also known as the Chenghe River), Chengbei River, Chengnan River, Longgang River, Dashui River, Dasha River, and Yucun River. Collectively, these rivers encompass over 70% of the basin's area, as illustrated in Fig.1.

The water quality of Yilong Lake has been assessed using monthly monitoring data collected from three distinct sections: east of the lake (provincial control), west of the lake (provincial control), and middle of the lake (national control) from 2016 to 2023. This data primarily originates from the National Real-time Data Distribution System for Automated Surface Water Quality Inspection (https://szzdjc.cnemc.cn:8070/GJZ/) and the Monthly Report on

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Water Quality Monitoring of Nine Plateau Lakes published by the Yunnan Provincial Department of Ecology and Environment (https://sthjt.yn.gov.cn/hjzl/9dgyhpsjjcyb/). The primary indicators for evaluating water quality encompass the permanganate index (PI), chemical oxygen demand (COD), five-day biochemical oxygen demand (BOD_5), ammonia nitrogen (NH_3-N), total nitrogen (TN), total phosphorus (TP), and chlorophyll a (Chla).

1.2 Evaluation methods

1.2.1 Mann-Kendall test. The Mann-Kendall test is a nonparametric statistical method utilized to assess the trend within a time series[11]. This test is characterized by its independence from specific distributional assumptions and its robustness against the influence of outliers. It is extensively employed in the analysis of trends in time series data related to precipitation, runoff, temperature, and water quality.

1.2.2 Kriging interpolation algorithm. The Kriging interpolation algorithm is a well-established and widely utilized method for spatial interpolation[12]. Initially proposed by South African engineer Danie G. Krige, this technique was first applied to soil science for spatial interpolation analysis in the 1980s. Subsequent theoretical advancements and experimental validations have significantly enhanced the reliability of the algorithm. The Kriging interpolation method offers the advantage of considering the relationship between predicted points and known data points, resulting in high estimation accuracy that objectively and accurately reflects the spatial distribution patterns. To ensure unbiased estimation throughout the process, the sum of the weights assigned to the neighboring samples is constrained to equal 1, and the ordinary Kriging spatial interpolation method can be expressed as follows:

$$Z(x_0)=\sum_{i=1}^{n}\lambda_i \times Z(x_i),\ \sum_{j=1}^{n}\lambda_i=1$$

where $Z(x_0)$ represents the value at the position x_0, while x_i denotes the value at the i-th position among the n points surrounding the estimated value point x_0. The term λ_i refers to the associated weighting factor, which signifies the contribution of each objective value to the estimated value $Z(x)$. Under the assumption that the estimates are unbiased (i.e., the mean of the valuation bias is equal to zero) and optimal (i.e., the variance of the valuation is minimized), it can be derived from the semivariance function of the variables, as expressed in the following formula:

$$\gamma(h)=\frac{1}{2N(h)}\sum_{i}^{N(h)}\left[Z(x_i)-Z(x_i+h)\right]$$

where $\gamma(h)$ denotes the semivariance, $N(h)$ represents the number of pairs of points separated by a distance of h, $Z(x_i)$ indicates the value at the position x_i, and $Z(x_i+h)$ refers to the value at a distance of (x_i+h).

2 Results and analysis

2.1 Analysis of interannual variation trends

The temporal variations in the primary water quality indicators of Yilong Lake from 2016 to 2023 are illustrated in Fig.2. Throughout this period, the water quality classification of Yilong Lake consistently fell within the severely degraded Class V category. The predominant pollutants identified include the PI, COD, BOD_5, NH_3-N, TN, and TP. The eutrophication index of Yilong Lake exhibited an increasing trend, rising from 35.32 in 2016 to 36.71 in 2023. Notably, the BOD_5, TN, and TP also demonstrated increasing trends. Specifically, the BOD_5 increased from 3.96 mg/L in 2016 to 4.70 mg/L in 2023, reflecting an annual growth rate of 18.80%. TN concentrations rose from 2.27 mg/L in 2016 to 2.29 mg/L in 2023, reflecting an annual increase rate of 0.82%. Similarly, TP levels increased from 0.057 9 mg/L in 2016 to 0.058 2 mg/L in 2023, corresponding to an annual growth rate of 0.49%. Transparency exhibited a slight decreasing trend, while Chla concentrations increased from 0.033 mg/m^3 in 2016 to 0.102 mg/m^3 in 2023, reflecting an annual growth rate of 0.26%. The primary contributors to the exceedance of water quality standards in the vicinity of Yilong Lake include urban domestic sewage, effluent from industrial parks, domestic waste generated by rural residents' production and daily activities, agricultural waste, wastewater from decentralized farming, domestic sewage, non-point source pollution from agricultural and rural areas, as well as point source discharges arising from urban activities and the soybean product processing industry.

The trend test calculations for the PI, COD, BOD_5, NH_3-N, TN, TP, Chla, and transparency in Yilong Lake were conducted using the Mann-Kendall test formula. The results of these calculations are presented in Table 1.

Yilong Lake exhibited a declining trend from 2016 to 2023, with the exception of BOD_5, TN and Chla, both of which demonstrated an increasing trend during the same period.

Table 1 Variation trend of water quality in Yilong Lake from 2016 to 2023

Water quality parameters	Mann-Kendall test	
	Z	Variation trend
PI	−0.532 4	Decreasing
COD	−0.235 0	Decreasing
BOD_5	4.605 4	Increasing
NH_3-N	−2.074 0	Decreasing
TN	0.653 3	Increasing
TP	2.292 9	Increasing
Chla	6.124 2	Increasing
Transparency	−4.412 7	Decreasing

2.2 Mutation test analysis

To conduct a comprehensive analysis of the mutation points across various time periods, the water quality data from 2016 to 2023 was subjected to the Mann−Kendall mutation test utilizing Matlab 2016 software, with a significance level set at 0.05. The findings of this analysis are presented in Fig.3.

As illustrated in Fig.3, the mutation points for PI from 2016 to 2023 were identified in August 2016 and June 2023. The mutation points for COD occurred in January and July 2016, as well as in March and September 2023. The mutation point for BOD_5 was recorded in July 2019. For NH_3-N, mutation points were observed in May 2017, January 2020, and November 2021. Mutation points for TN were noted in April 2016 and in January, February, and August 2023. The mutation point for TP was identified in January 2021, while the mutation point for Chla was recorded in August 2017. Finally, the mutation point for transparency was observed in February 2019.

The mutation points for the PI, COD, BOD_5, NH_3-N, TN, TP, and transparency were all situated within the significant confidence intervals (α=0.05), suggesting that these mutations were not statistically significant. Conversely, one mutation point for Chla was found outside the significant confidence interval (α=0.05), indicating that this mutation was statistically significant. In conclusion, the frequency and timing of mutations in the water quality indicators of Yilong Lake exhibited variability, predominantly occurring between the

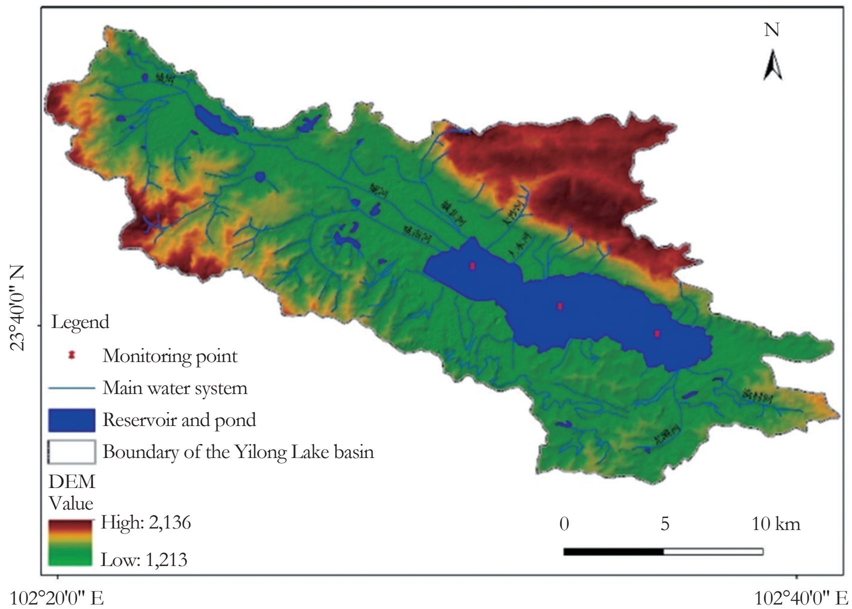

Fig.1 Sketch of the study area

years 2016-2017 and 2019-2021.

2.3 Spatial distribution characteristics

The spatial distribution maps for PI, COD, BOD_5, NH_3-N, TN, TP, Chla, and transparency were generated through the analysis of key water quality indicators at three monitoring sites within Yilong Lake, utilizing GIS spatial interpolation techniques (Fig.4).

As illustrated in Fig.4, the PI, COD, TN, and Chla concentrations exhibited the following spatial distribution: east of the lake > middle of the lake > west of the lake. In contrast, the BOD_5 and TP levels were observed in the order of west of the lake > east of the lake > middle of the lake. Additionally, NH_3-N concentrations were ranked as east of the lake > west of the lake > middle of the lake, while transparency was recorded in the sequence of west of the lake > middle of the lake > east of the lake.

The analysis of the pollution load entering

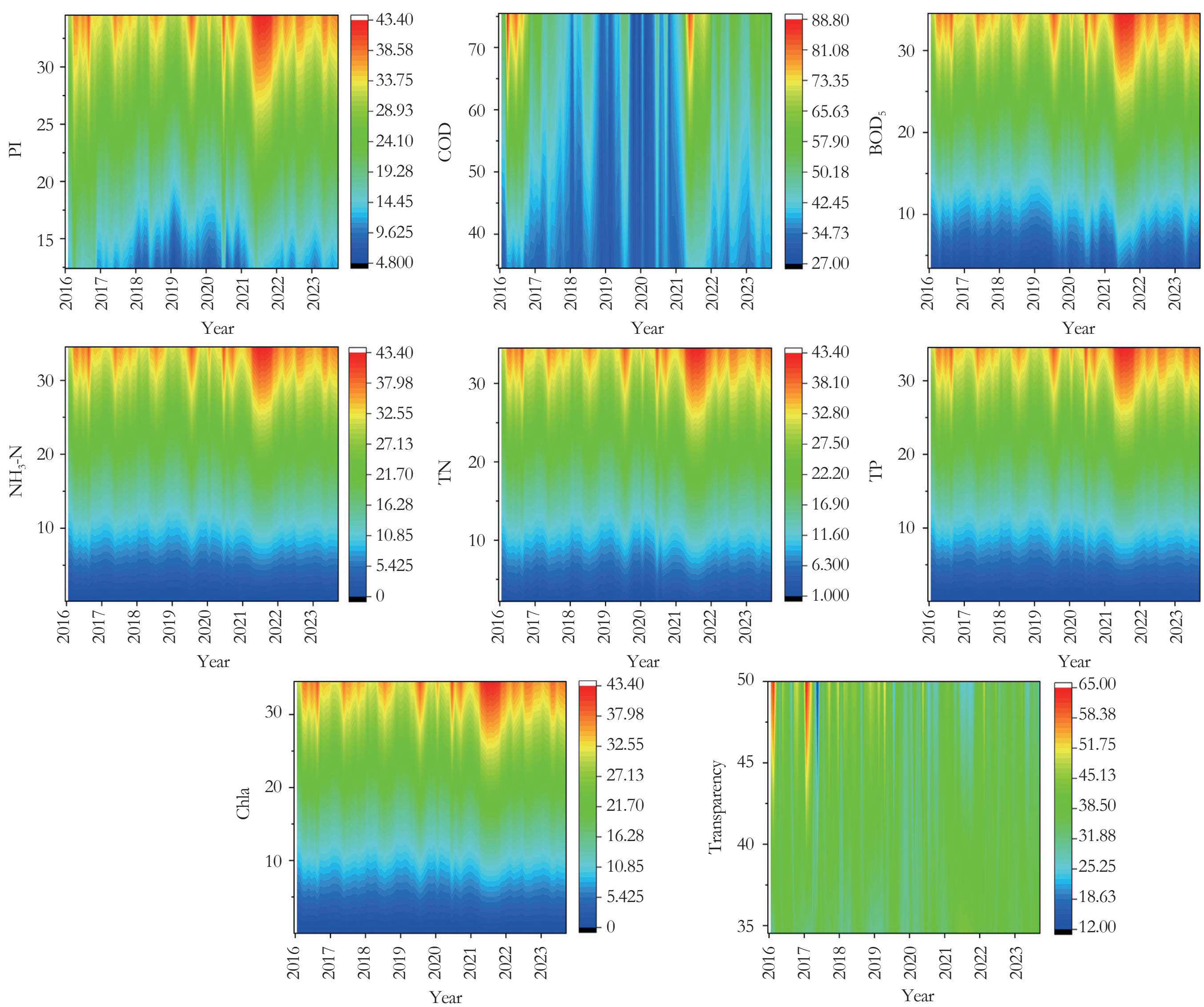

Fig.2 Variations in major water quality indicators of Yilong Lake from 2016 to 2023

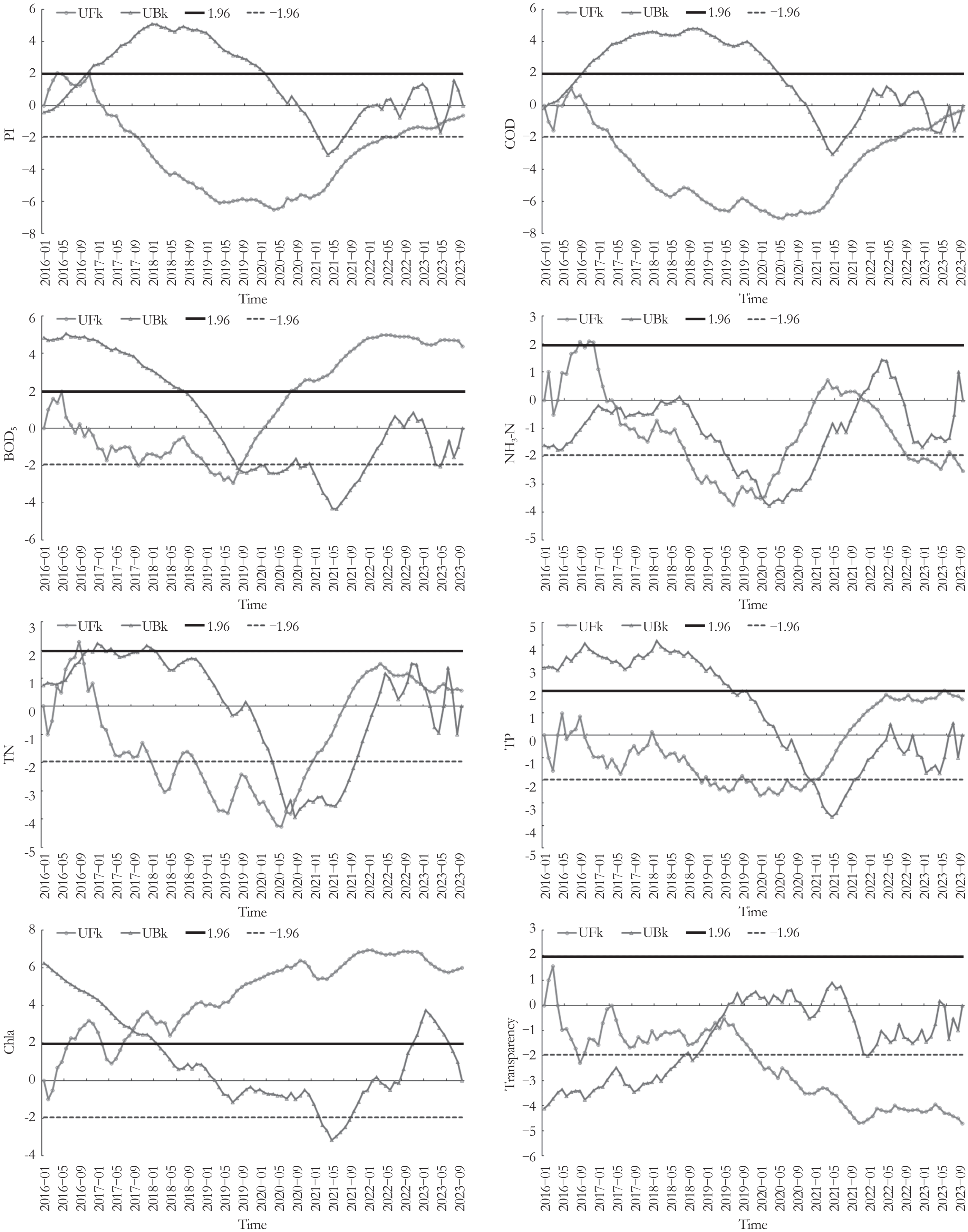

Fig.3 Mann–Kendall mutation test for major water quality data of Yilong Lake

Yilong Lake revealed that the primary contributors to COD were free-ranging rural livestock and poultry, as well as non-point source pollution from rural activities, which accounted for 28.10% and 23.35% of the total inflow into the lake, respectively. This was followed by industrial enterprise pollution, which constituted 17.05% of the total inflow. Additionally, urban domestic pollution and large-scale livestock and poultry breeding contributed 9.52% and 8.58% of the total inflow, respectively. NH_3-N primarily originated from rural domestic pollution, which constituted 41.26% of the total inflow into the lake. This was followed by free-ranging rural livestock and poultry, contributing 29.09% of the total inflow. Additionally, large-scale livestock and poultry breeding, urban domestic pollution, and industrial enterprise pollution accounted for 7.98%, 4.72%, and 2.92% of the total inflow, respectively. The primary sources of TN pollution were identified as rural domestic waste and agricultural fertilizers, which contributed 30.05% and 28.09%, respectively, to the total nitrogen inflow into the lake. Additionally, urban domestic pollution, industrial enterprise pollution, and large-scale livestock and poultry breeding accounted for 6.14%, 4.76%, and 4.12% of the total inflow into the lake, respectively. The primary sources of TP inflow into the lake were rural domestic pollution and the loss of fertilizers from agricultural lands, which contributed 33.85% and 28.09% of the total inflow, respectively. This was followed by free-ranging rural livestock and poultry, which accounted for 15.19% of the total inflow. Additionally, urban domestic pollution, large-scale livestock and poultry breeding, and industrial enterprise pollution contributed 9.86%, 4.33%, and 3.74% of the total inflow into the lake, respectively.

The pollution in the eastern part of Yilong Lake primarily originated from domestic sewage and free-ranging livestock and poultry. In the central part of the lake, the pollution was predominantly attributed to domestic sewage and agricultural water withdrawal from the Gaojiawan, Doudiwan, and Dashuitian regions. Conversely, the western part of the lake was chiefly affected by domestic sewage from Baoxiu Town, overflow sewage from industrial parks, wastewater from villages situated along the shoreline, water withdrawal from arrowhead fields, domestic sewage from residential areas on the outskirts of the city, wastewater from rural villages in Loujiazhai and Daruicheng, and high-concentration wastewater from soybean processing, resulting in a substantial negative impact on the western part of Yilong Lake and further deteriorating the water quality.

3 Countermeasures

3.1 Strengthening the construction of a precise pollution control system, and controlling pollution sources and intercepting pollution to reduce the pollution load entering lakes

Point source pollutant control aims to mitigate the pollution load entering the lake from the production wastewater generated by soybean processing enterprises within the basin, domestic pollution in the county, specifically in Baoxiu and Baxin towns, and aquaculture pollution along the Chenghe River and Yilong Lake. Songcun section of the Chenghe River, along with the Darecheng and Dashuicun regions, has been identified as critical zones for the implementation of industrial pollution control measures. Additionally, rural activities and livestock breeding contribute significantly to the pollution load, accounting for approximately 50% of the COD and TN entering the lake. These factors represent the primary sources of pollution within the basin. It is therefore recommended to adopt a strategy "focused on breakthroughs, integrating both point and non-point source controls", to strictly control the pollution loads entering the lake. According to the primary sources of pollution contributing to the lake's pollution load, and combined with the feasible conditions of the project, we should manage the concentrated pollution areas within agricultural and rural regions, specifically the Songcun section of the Chenghe River and the northern bank of Yilong Lake. By integrating ecological storage and regulation systems, constructing ecological wetlands, and effectively linking sewage interception networks, it is anticipated that the pollution load entering the lake can be maintained at a relatively low level.

3.2 Strengthening the protection and restoration of river and lake ecosystems to gradually restore their functions

In regions where ponds are converted back into lakes, particularly along the lakeshore and at the estuaries of significant rivers that discharge into the lake, such as the Chenghe River, Chengnan River, Chengbei River, Dashui River, and Longgang River, ecological wetlands and water storage systems should be developed in accordance with local conditions. Additionally, non-point source pollutants from the inflow and outflow of these rivers should undergo further purification prior to entering Yilong Lake. This approach will simultaneously establish an ecological barrier to protect Yilong Lake. It is essential to develop and execute systematic strategies for the protection and restoration of river basin ecosystems. These strategies should be tailored to local conditions and involve the gradual implementation of ecological restoration and construction projects in mountainous regions adjacent to lake surfaces, in order to improve the quality of forest ecosystems and enhance ecosystem service functions, including water conservation and soil preservation.

3.3 Strengthening ecological water replenishment and water recycling to enhance the capacity of the water environment

The issue of resource-based water scarcity in the Yilong Lake basin is significant. In addition to reducing pollutants, it is essential to implement measures such as ecological water replenishment from adjacent basins, water conservation strategies, and the recycling of water resources to augment the volume of clean water entering the lake. In the short term, it is imperative to restore the lake to a reasonable and normal operating water level as swiftly as possible. This restoration should facilitate an outflow to discharge the pollution load that has accumulated over many years, thereby improving the hydrodynamic conditions of the lake. Furthermore, these efforts will enhance the water environmental capacity and the self-purification ability of the lake, thus improving the overall quality of the water environment.

3.4 Strengthening scientific and technological support and comprehensive regulatory safeguards to ensure that water quality is stable and meets standards

Given the uncertainties associated with the simulation of future scenarios through model prediction methods, particularly those arising from extreme meteorological conditions that can significantly alter hydrometeorological parameters, alongside various risks inherent in project implementation, it is essential to concurrently develop an ecological environment observation network for Yilong Lake, in order to enhance the effectiveness of water quality improvement efforts for Yilong Lake. Additionally, it is important to carry out research on the water balance of river basins and the refined dispatching of water resources, and the impact of different operating water levels and water replenishment methods on the ecological environment of lake water, implement lake ecosystem restoration technologies and

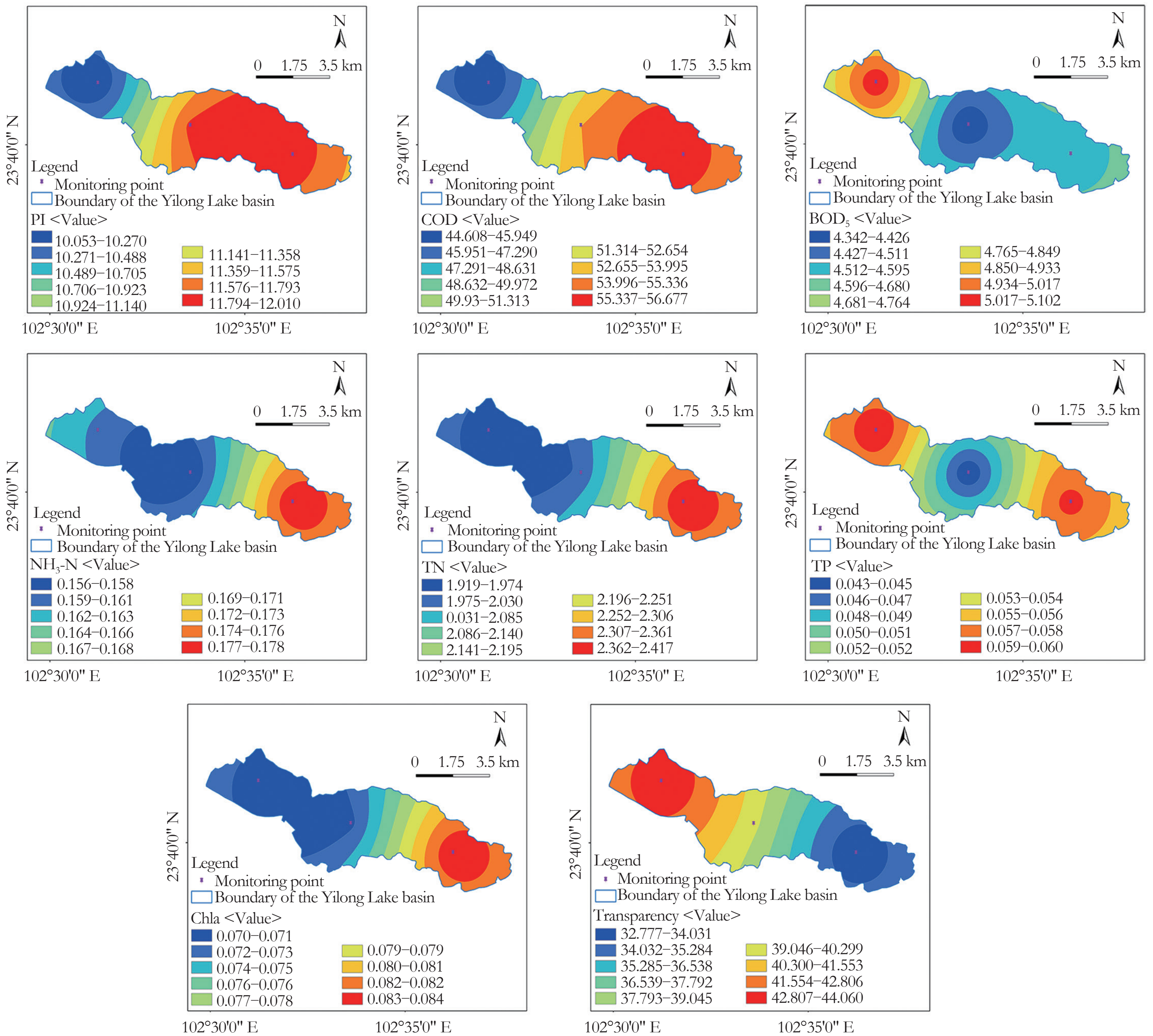

Fig.4 Spatial interpolation of the main water quality indicators of Yilong Lake

engineering demonstrations, and investigate the restoration of lake ecosystems and the treatment techniques for internal pollution sources. Additionally, there is a need to adjust and optimize the industrial structure and spatial organization of river basins, while controlling the impacts of development and utilization on the ecological environment and water quality of lakes. These efforts are necessary to ensure that water quality consistently meets established standards and to enhance the functional integrity of lake ecosystems.

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built environment, a break in the biological migration corridor has formed, resulting in an almost complete loss of its bird-inhabiting function. Although the core mausoleum area had a favorable vegetation foundation, the dense commemorative building complexes and tourist routes generated continuous sources of acoustic and light interference. It was recommended that a buffer zone could be established to re-configure the interface between human and bird activities.

When conducting bird-watching activities in the Ming Tombs area, it was essential to understand the dynamic pattern characterized by "core radiation from the northern side of the reservoir and gradient responses of seasonal habitats", and establish a spatio-temporal coordinated observation system. In the spring mornings, the focus should be on the mixed coniferous and broad-leaved forests in the shallow mountain areas. This allowed for the capture of the reproductive rhythms of forest birds as they shuttled and built nests on the sunny slopes. During summer, by venturing deep into the dense forests of the back mountains, the humid period after rainfall could be utilized to analyze the foraging cooperation and acoustic-landscape positioning of co-occurring species groups within the three-dimensional vegetation structure of the mixed forests. In autumn, the focus was shifted to the southern fracture-restoration areas. In the newly-established shrubbery, the corridor-stepping-stone effect formed by migratory species that rely on the reconstruction of native vegetation was traced. In winter, the clear sky after snowfall was utilized to observe the adaptive behaviors of birds towards cultural-heritage elements such as glazed eaves and stone-carved pedestals within the buffer zones of ancient buildings. This approach aimed to uncover the symbiotic potential between artificial structures and natural survival.

In the future, the planning of bird-watching sites should be more comprehensively integrated with fields such as ecotourism and biodiversity conservation. It is crucial not only to concentrate on the scientific layout and infrastructure construction of bird-watching sites but also to emphasize the development of diverse ecotourism products and services. By integrating bird-watching activities with science education and cultural experiences, the overall value of bird-watching can be enhanced. Furthermore, strengthening collaboration with relevant government agencies and social organizations is essential. This cooperation can facilitate the practical implementation and dissemination of the planning outcomes of bird-watching sites. Simultaneously, it is necessary to establish and refine a sound management mechanism and regulatory framework for bird-watching activities, thereby promoting the sustainable development of bird-watching initiatives[15].

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