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Spatial changes and driving factors of lake water quality in Inner Mongolia, China

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Abstract: Lakes play important roles in sustaining the ecosystem and economic development in Inner Mongolia Autonomous Region of China, but the spatial patterns and driving mechanisms of water quality in lakes so far remain unclear. This study aimed to identify the spatial changes in water quality and the driving factors of seven lakes (Juyanhai Lake, Ulansuhai Lake, Hongjiannao Lake, Daihai Lake, Chagannaoer Lake, Hulun Lake, and Wulannuoer Lake) across the longitudinal axis (from the west to the east) of Inner Mongolia. Large-scale research was conducted using the comprehensive trophic level index (TLI (Σ)), multivariate statistics, and spatial analysis methods. The results showed that most lakes in Inner Mongolia were weakly alkaline. Total dissolved solids and salinity of lake water showed obvious zonation characteristics. Nitrogen and phosphorus were identified as the main pollutants in lakes, with high average concentrations of total nitrogen and total phosphorus being of 4.05 and 0.21 mg/L, respectively. The values of TLI (Σ) ranged from 49.14 to 71.77, indicating varying degrees of lake eutrophication, and phosphorus was the main driver of lake eutrophication. The lakes of Inner Mongolia could be categorized into lakes to the west of Daihai Lake and lakes to the east of Daihai Lake in terms of salinity and TLI (Σ). The salinity levels of lakes to the west of Daihai Lake exceeded those of lakes to the east of Daihai Lake, whereas the opposite trend was observed for lake trophic level. The intensity and mode of anthropogenic activities were the driving factors of the spatial patterns of lake water quality. It is recommended to control the impact of anthropogenic activities on the water quality of lakes in Inner Mongolia to improve lake ecological environment. These findings provide a more thorough understanding of the driving mechanism of the spatial patterns of water quality in lakes of Inner Mongolia, which can be used to develop strategies for lake ecosystem protection and water resources management in this region.

Keywords: salinity; lake eutrophication; lake water quality; comprehensive trophic level index; anthropogenic activities; Daihai Lake; Inner Mongolia

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1 Introduction

Lakes are an important component of water resources and play an irreplaceable role in maintaining ecosystem balance and economic development, particularly in arid and semi-arid

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areas (Kopprio et al., 2014; Rather and Dar, 2020; Wang et al., 2021). Therefore, the sustainable utilization of lake water resources is the basis of the future social development in many regions, and the safety of lake water quality directly affects the quality of life for residents. Lake water quality is affected by both natural conditions (such as precipitation, weathering, and soil erosion) and anthropogenic activities (such as industrial activity, agricultural activity, and urbanization) (Leon-Munoz et al., 2013; Shen et al., 2017; Sekaluvu et al., 2018; Li et al., 2020). However, one-third of the world's lakes are under enormous anthropogenic pressure (Mammides, 2020). Environmental problems have become increasingly prominent with rapid increases in human populations and the development of industry, agriculture, and urbanization. In particular, the pollution of lakes has become an urgent environmental problem globally (Wen et al., 2016; Du et al., 2018; Sacdal et al., 2020; Kakade et al., 2021). Therefore, it is necessary to prevent and mitigate lake pollution for the sustainable utilization of lake water resources.

Water quality assessment can be used to understand the quality status of a water source and to identify the pollution factors, and this approach is important for the control of water pollution and water resources management (Li et al., 2007; Zhang et al., 2019; Rosca et al., 2020; Varol, 2020). There have been many studies in recent years on lake water quality assessment and its driving factors, as well as the identification of pollution sources, for example, Tana Lake in Ethiopia (Tibebe et al., 2019), Cajititlán Lake in Mexico (Gradilla-Hernandez et al., 2019), Mariut Lake in Egypt (Shreadah et al., 2020), Mettur Reservoir in India (Saha et al., 2021), and Chagan Lake (Liu et al., 2019) and Shahu Lake (Tian et al., 2020) in China. Although these studies on lake water quality and its driving factors are important, most of them focused on individual lakes. There are differences in water quality and its driving factors among the lakes in different regions, especially at large scales (Li et al., 2007; Ding et al., 2015; Qu et al., 2020). Therefore, it is much valuable to explore the spatial pattern of lake water quality and its formation mechanism through water quality assessment, which will help to maintain the ecological function of lakes and support the scientific decision-making of relevant government departments.

Lakes in Inner Mongolia Autonomous Region of China are an important part of the ecological security barrier in northern China. These lakes are of great significance to regional ecological environment security, climate regulation, and social and economic development. In addition, Inner Mongolia encompasses a large area and contains typical semi-arid and arid climate areas, and the water quality conditions of lakes are different among the different areas (Wang et al., 2015; Zhang et al., 2019; Wang et al., 2020). Therefore, Inner Mongolia is an ideal study region for examining the spatial changes of lake water quality. In recent years, the deterioration of lake water quality caused by climate change and the rapid development of the regional economy and urbanization has attracted more and more scientific attention (Liu and Wang, 2014; Wang et al., 2015; Yang et al., 2019). There are some studies on the water quality of lakes in Inner Mongolia, such as Hulun Lake (Chen et al., 2012; Wang et al., 2020), Dalinuoer Lake (Liu et al., 2015; Zhen et al., 2015), and Ulansuhai Lake (Zhang et al., 2019; Jin et al., 2020). Since these studies mainly focused on individual lakes and nutrient indicators, there remains a lack of comprehensive research on the spatial patterns and driving mechanisms of water quality in lakes across the entire Inner Mongolia. An unclear understanding of the spatial changes in lake water quality has also restricted the protection and management of local lakes. Considering that the water quality of lakes is undergoing rapid changes, it is necessary to comprehensively explore the water quality of lakes in this region using the latest observation data, which can be used to formulate adaptive pollution control and water resources management strategies.

The main aims of the present study are to: (1) comprehensively and scientifically evaluate the water quality of lakes in Inner Mongolia; and (2) analyze the spatial patterns and driving factors of lake water quality in Inner Mongolia. The results of this study can provide a scientific reference for lake pollution control, water resources management, and ecosystem protection in Inner Mongolia, as well as improve the understanding of spatial patterns in water quality among different lakes in semi-arid and arid climate areas.

2 Materials and methods

2.1 Study area

Inner Mongolia is a landlocked region in northern China and lies southeast of the Mongolian Plateau in Central Asia, falling within the coordinates of 97°12′–126°04′E and 37°24′–53°23′N. The shape of Inner Mongolia is long and narrow, and the terrain extends diagonally from the northeast to the southwest (Fig. 1). The region has a plateau type landform with an average altitude of approximately 1000 m, collectively referred to as the Inner Mongolia Plateau. Inner Mongolia has a wide range of land use types, including grassland, construction land, and arable land. It should be noted that Inner Mongolia contains vast grassland and arable land areas, and has developed animal husbandry. The climate of the region is characterized by long and cold winters, windy and dry springs, short and hot summers, and a sharp drop of temperature in autumn. The long and narrow shape of the region in a longitudinal direction leads to changes in climate from semi-arid in the east to arid in the west, corresponding to a decrease in precipitation and an increase in evaporation. Inner Mongolia contains over 1000 rivers, and there are also many lakes distributed across the region, which play an important role in the stability of regional ecosystem (Tao et al., 2015).

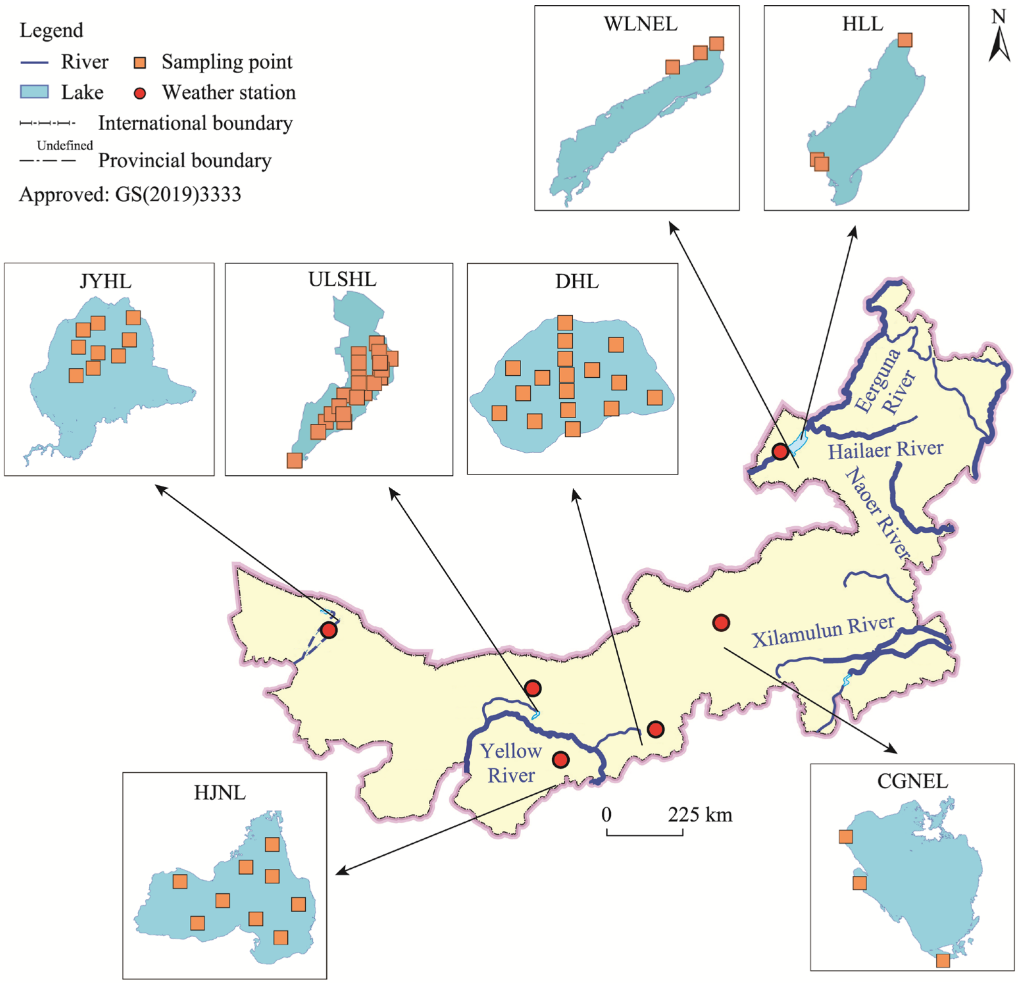

Fig. 1 Geographical locations of the selected seven lakes and the sampling points in Inner Mongolia in the present study. JYHL, Juyanhai Lake; ULSHL, Ulansuhai Lake; HJNL, Hongjiannao Lake; DHL, Daihai Lake; CGNEL, Chagannaoer Lake; HLL, Hulun Lake; WLNEL, Wulannuoer Lake. Note that the figure is based on the standard map (GS(2019)3333) of the Map Service System (http://bzdt.ch.mnr.gov.cn/), and the standard map had not been modified.

The present study selected seven typical lakes longitudinally across Inner Mongolia from the west to the east, namely Juyanhai Lake, Ulansuhai Lake, Hongjiannao Lake, Daihai Lake, Chagannaoer Lake, Hulun Lake, and Wulannuoer Lake. Figure 1 and Table 1 show detailed information about these lakes.

Table 1 Description of the selected lakes in Inner Mongolia

Lake	Abbreviation	Longitude	Latitude	Area (km^2)	Recharge river
Juyanhai Lake	JYHL	101°12′–101°20′E	42°15′–42°20′N	42.40	Heihe River
Ulansuhai Lake	ULSHL	108°43′–108°57′E	40°47′–41°03′N	293.00	Yellow River
Hongjiannao Lake	HJNL	109°50′–109°56′E	39°04′–39°08′N	36.06	Donghulusu River and Zhasake River
Daihai Lake	DHL	112°37′–112°45′E	40°33′–40°37′N	55.00	Gongba River and Tiancheng River
Chagannaoer Lake	CGNEL	114°58′–115°03′E	43°25′–43°29′N	31.52	Gaogusitai River and Engeer River
Hulun Lake	HLL	116°58′–117°48′E	48°33′–49°20′N	2339.00	Kelulun River and Wuerxun River
Wulannuoer Lake	WLNEL	117°22′–117°32′E	48°16′–48°22′N	29.43	Wuerxun River

2.2 Sample collection and analysis

The present study collected water samples from the selected seven lakes longitudinally across Inner Mongolia from July to August in 2020 when all lakes were in the non-freezing period. Water samples were collected from 3–21 points in each lake, with a total of 66 water samples (Fig. 1). Sample bottles were rinsed with raw water three times before sampling. A 1500 mL plexiglass sampler was used to collect water sample from a depth of 0.5 m below water surface. At each sampling point, two samples were collected in two 500 mL polyethylene bottles and one sample was collected in a 50 mL glass bottle. After collection, each sample bottle was immediately sealed with parafilm and transported back to the laboratory for analysis. The longitude and latitude coordinates and elevation of the sampling points were accurately measured using a Global Positioning System (GPS) (Table 1).

We adopted the following representative water quality parameters considering the significant risks posed to the water environment by surface water pollutants: pH, total dissolved solids (TDS; g/L), salinity (g/L), dissolved oxygen (DO; mg/L), transparency (SD; m), total phosphorus (TP; mg/L), total nitrogen (TN; mg/L), ammonia nitrogen (NH_4^+-N; mg/L), chlorophyll-a (Chl-a; μg/L), and permanganate index (COD_{Mn}; mg/L). Parameters of pH, TDS, salinity, and DO are important indicators that reflect the overall situation of water quality (Liu et al., 2020; Ren et al., 2022). Parameters of TP, TN, NH_4^+-N, and Chl-a are key indicators of lake eutrophication (Tian et al., 2020; Saha et al., 2021). COD_{Mn} reflects the organic pollution in water (Zhang et al., 2019; Geng et al., 2021).

The same sampling methods and equipment were applied to all lake water samples. Parameters of pH, TDS, salinity, and DO were measured at the sampling points using the WTW Multi 3630 multimeter (WTW GmbH, Weilheim, Germany) with measurement accuracies of ±0.004, ±0.5%, ±0.5%, and ±0.5%, respectively. SD was estimated by measures of water transparency at the sampling points using a Secchi disc. TP, TN, NH_4^+-N, COD_{Mn}, and Chl-a were measured by an ammonium molybdate spectrophotometry (UV-2600 PC, Shimadzu, Kyoto, Japan), an alkaline potassium persulfate digestion UV spectrophotometry (UV-2600 PC, Shimadzu, Kyoto, Japan), the Nessler reagent colorimetry, the potassium permanganate titration, and an acetone extraction spectrophotometry (UV-2600 PC, Shimadzu, Kyoto, Japan), respectively.

Climate data including annual mean temperature (2010–2020), annual precipitation (2010–2020), annual sunshine hours (2010–2020), and annual evaporation (2000–2020) of the selected lakes were obtained from the China Meteorological Data Network (http://data.cma.cn/). The area data of grassland, construction land, and arable land in 2019 were obtained from the Third China Land Survey Key Data Bulletin (Ministry of Natural Resources of the People's Republic of China, 2021).

2.3 Comprehensive trophic level index (TLI (Σ))

The present study used the TLI (Σ) to evaluate the levels of lake eutrophication, containing evaluation parameters of Chl-a, TP, TN, SD, and COD_{Mn}. We divided the lakes into six categories according to the trophic level: (I) oligotrophic, TLI (Σ)<30; (II) mesotrophic, 30≤TLI (Σ)≤50; (III) eutrophic, TLI (Σ)>50; (IV) light eutrophic, 50<TLI (Σ)≤60; (V) middle eutrophic, 60<TLI (Σ)≤70; and (VI) hypereutrophic, TLI (Σ)>70. TLI (Σ) was calculated as follows:

$$\text{TLI}\ (\Sigma)=\sum_{j=1}^{m} W_j \times \text{TLI}\ (j), \tag{1}$$

where TLI (Σ) is the comprehensive trophic level index; W_j is the relative weight of the trophic level index of the j^{th} parameter (Wang et al., 2002; Li et al., 2018); and TLI (j) is the trophic level index of the j^{th} parameter.

The trophic level of each evaluation parameter was calculated as:

$$\text{TLI}\,(\text{Chl-a}) = 10\times(2.5+1.086\ln(\text{Chl-a})), \tag{2}$$

$$\text{TLI}\,(\text{TP}) = 10\times(9.436+1.624\ln\text{TP}), \tag{3}$$

$$\text{TLI}\,(\text{TN}) = 10\times(5.453+1.694\ln\text{TN}), \tag{4}$$

$$\text{TLI}\,(\text{SD}) = 10\times(5.118-1.94\ln\text{SD}), \tag{5}$$

$$\text{TLI}\,(\text{COD}_{\text{Mn}}) = 10\times(0.109+2.661\ln\text{COD}_{\text{Mn}}). \tag{6}$$

2.4 Data analysis

The data obtained in this study were statistically analyzed using Excel 2016, Origin 2021, ArcGIS 10.2, and SPSS 25.0 software. Spatial trend analysis in ArcGIS 10.2 was used to explore the spatial variations in the water quality of lakes in Inner Mongolia, and hierarchical cluster analysis was applied to determine the spatial patterns in the water quality of lakes in the study area. Pearson correlation analysis was utilized to analyze the relationships between lake water quality parameters and TLI (Σ), as well as the relationships of the spatial variations in lake water quality with climate indicators and land use indicators.

3 Results

3.1 Spatial variations in lake water quality parameters

Figure 2 shows a histogram of the water quality parameters of lakes in Inner Mongolia from the west to the east. The pH of lake water ranged from 8.50 to 9.43, with an average value of 8.87 (±0.36), indicating that lake water in Inner Mongolia was generally weakly alkaline and showed a relatively stable spatial variation (Fig. 2a). The values of TDS, salinity, and SD ranged from 0.72 to 22.75 g/L, 0.30 to 13.81 g/L, and 0.11 to 3.89 m, respectively (with average values of 6.58 (±7.88) g/L, 3.77 (±4.83) g/L, and 1.16 (±1.32) m, respectively); all these parameters exhibited similar spatial zonation. Daihai Lake and lakes to the west of Daihai Lake showed higher TDS, salinity, and SD, compared to lakes to the east of Daihai Lake (Fig. 2b–d). The DO concentrations of lake water in the study area were relatively high and showed a clear spatial zonation, ranging from 7.14 to 12.36 mg/L (with an average value of 8.33 (±1.85) mg/L). The DO concentrations of Daihai Lake and lakes to the west of Daihai Lake were obviously lower than the concentrations of lakes to the east of Daihai Lake (Fig. 2e).

The TN concentrations of lake water ranged from 2.39 to 8.71 mg/L, with an average value of 4.05 (±2.19) mg/L, exceeding the class V (1.50 mg/L<TN≤2.00 mg/L) in the Environmental Quality Standards for Surface Water of the People's Republic of China (standard number: GB3838-2002; http://www.cnemc.cn/jcgf/shj/200801/t20080128_647287.shtml). The TN concentration of Daihai Lake was much higher than those of other lakes (Fig. 2f). The TP concentrations of lake water ranged from 0.04 to 0.56 mg/L (high in the east and low in the west), with an average value of 0.21 (±0.20) mg/L (Fig. 2g). Generally, TP was relatively high in lake

water, exceeding the class V (0.10 mg/L<TP≤0.20 mg/L) in the Environmental Quality Standards for Surface Water of the People's Republic of China (GB3838-2002). In addition, except for Ulansuhai Lake, the TP concentrations of other six lakes were between the class IV (0.05 mg/L<TP≤0.10 mg/L) and class V in the Environmental Quality Standards for Surface Water of the People's Republic of China (GB3838-2002); among these six lakes, TP concentrations were especially high in Wulannuoer Lake and Hulun Lake. NH_4^+-N concentrations ranged from 0.04 to 1.94 mg/L, with an average value of 0.69 (±0.76) mg/L. Daihai Lake, Hongjiannao Lake, and

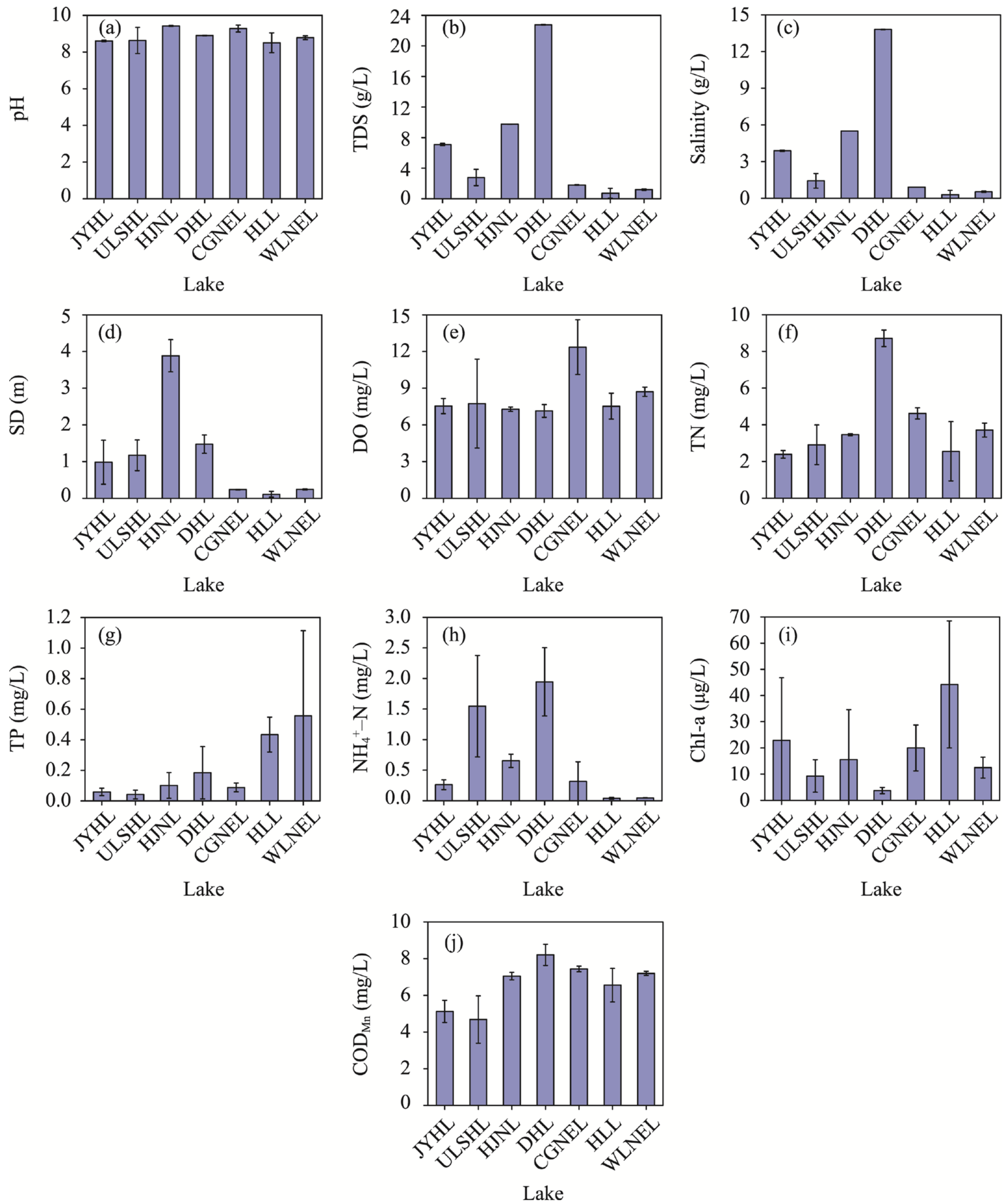

Fig. 2 Various in water quality parameters of the selected seven lakes in Inner Mongolia. (a), pH; (b), total dissolved solids (TDS); (c), salinity; (d), transparency (SD); (e), dissolved oxygen (DO); (f), total nitrogen (TN); (g), total phosphorus (TP); (h), ammonia nitrogen (NH_4^+-N); (i), chlorophyll-a (Chl-a); (j), permanganate index (COD_{Mn}). JYHL, Juyanhai Lake; ULSHL, Ulansuhai Lake; HJNL, Hongjiannao Lake; DHL, Daihai Lake; CGNEL, Chagannaoer Lake; HLL, Hulun Lake; WLNEL, Wulannuoer Lake. The lakes are shown on the *x*-axis from the left to the right in order of their geographical locations from the west to the east. Bars mean standard deviations.

Ulansuhai Lake showed relatively high concentrations of NH_4^+-N (Fig. 2h). The Chl-a concentrations of lake water in the study area ranged from 3.70 to 44.23 μg/L, with an average value of 18.31 (±13.11) μg/L. Liu (2011) classified lake eutrophication according to the Chl-a threshold of 10.00 μg/L, pointing out that the Chl-a concentration of lake water in Inner Mongolia was high. The highest concentration of Chl-a was observed in Hulun Lake (Fig. 2i). The COD_{Mn} concentrations of lake water ranged from 4.68 to 8.21 mg/L, with an average value of 6.61 (±1.27) mg/L, falling in the class IV (6.00 mg/L<COD_{Mn}≤10.00 mg/L) in the Environmental Quality Standards for Surface Water of the People's Republic of China (GB3838-2002). This result indicated that the COD_{Mn} concentrations of lake water were relatively high and showed little spatial variation in Inner Mongolia (Fig. 2j).

3.2 Lake eutrophication

The values of TLI (Σ) ranged from 49.14 to 71.77, with an average value of 58.77 (±8.91), indicating that some lakes in Inner Mongolia experienced a eutrophic level. Figure 3 showed that Hulun Lake had the highest eutrophic level with a TLI (Σ) of 71.77, falling into the hypereutrophic category. The TLI (Σ) values of Wulannuoer Lake and Chagannaoer Lake were 66.64 and 64.23, respectively, which were classed as middle eutrophic level. The TLI (Σ) values of Daihai Lake and Juyanhai Lake were 57.24 and 52.89, respectively, which were classed as light

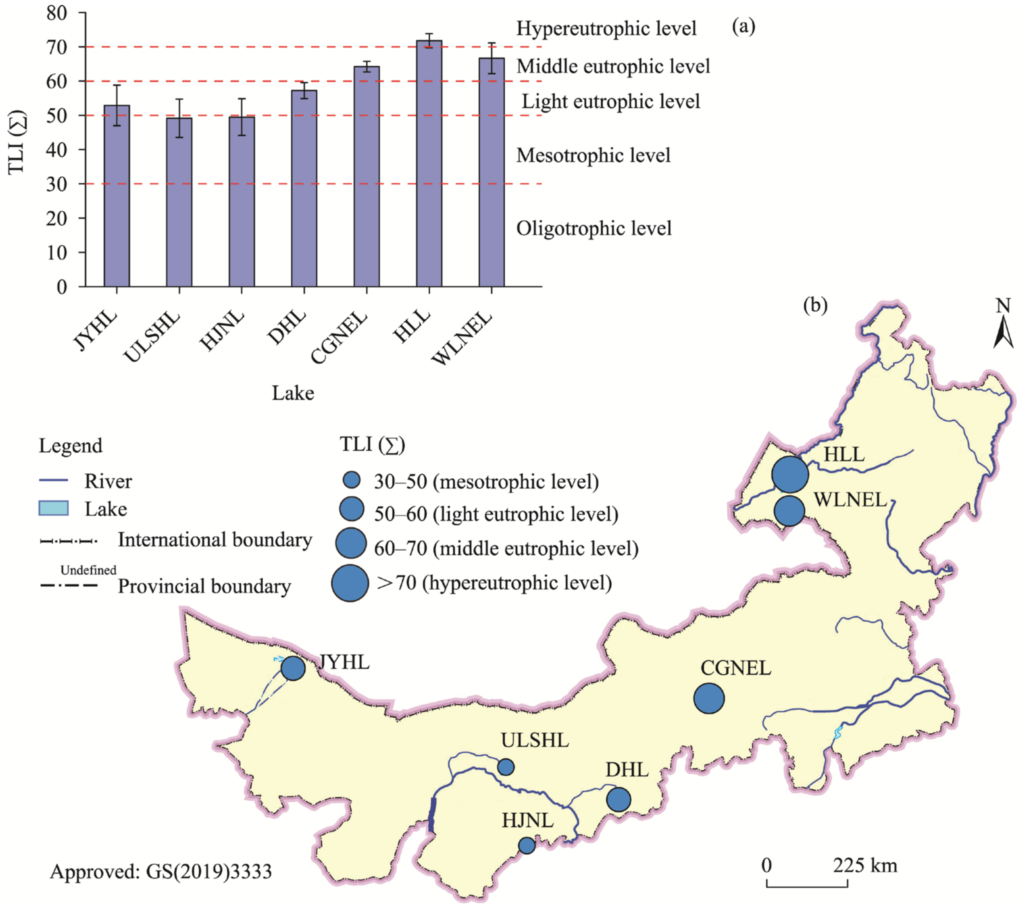

Fig. 3 Comprehensive trophic level index (TLI (Σ)) of lakes in Inner Mongolia. (a), spatial distribution of TLI (Σ) values of the seven selected lakes; (b), a histogram of the TLI (Σ) values of the seven selected lakes. JYHL, Juyanhai Lake; ULSHL, Ulansuhai Lake; HJNL, Hongjiannao Lake; DHL, Daihai Lake; CGNEL, Chagannaoer Lake; HLL, Hulun Lake; WLNEL, Wulannuoer Lake. Bars mean standard deviations. Note that the figure is based on the standard map (GS(2019)3333) of the Map Service System (http://bzdt.ch.mnr.gov.cn/), and the standard map had not been modified.

eutrophic level. However, TLI (Σ) of Daihai Lake was very close to the middle eutrophic level, indicating that this lake faced a risk of moving to a middle eutrophic level. The trophic levels of Hongjiannao Lake and Ulansuhai Lake were relatively low, with TLI (Σ) values of 49.50 and 49.14, respectively, and both lakes were classified as mesotrophic. However, the TLI (Σ) values of Hongjiannao Lake and Ulansuhai Lake were very close to the eutrophic level, indicating that the two lakes had a risk of moving into a eutrophic level. In general, the serious eutrophic lakes were mainly distributed in the eastern part of Inner Mongolia, with TLI (Σ) showing an increasing trend from the west to the east.

3.3 Spatial patterns of lake water quality

The results of the present study showed differences in water quality among the lakes of Inner Mongolia. However, clear differences in salinity and TLI (Σ) among lakes were also observed. Therefore, spatial trend analysis was conducted for salinity and TLI (Σ) (Fig. 4). Salinity exhibited a significant decreasing trend on the *YZ* plane (the projection plane of salinity or TLI (Σ) versus dimension) in Figure 4 (R^2=0.17, P<0.01), i.e., salinity decreased significantly from the south to the north in Inner Mongolia, whereas there was no significant change in salinity on the *XZ* plane (the projection plane of salinity or TLI (Σ) versus longitude). TLI (Σ) showed significant increasing trends on the *YZ* (R^2=0.43, P<0.01) and *XZ* (R^2=0.29, P<0.01) planes, i.e., TLI (Σ) increased significantly from the south to the north and from the west to the east in Inner Mongolia. In addition, the hierarchical clustering analysis of salinity and TLI (Σ) indicated that lakes in Inner Mongolia could be clearly divided into two categories at a Euclidean distance of <20 (Fig. 5): (1) lakes to the west of Daihai Lake and (2) lakes to the east of Daihai Lake. Lakes to the west of Daihai Lake are Juyanhai Lake, Ulansuhai Lake, Hongjiannao Lake, and Daihai Lake from the west to the east, whereas lakes to the east of Daihai Lake are Chagannaoer Lake, Hulun Lake, and Wulannuoer Lake from the west to the east. Generally speaking, clear spatial zonal characteristics in lake water quality were observed in Inner Mongolia. Interestingly, the salinity of lakes to the west of Daihai Lake was higher than that of lakes to the east of Daihai Lake, whereas the opposite pattern was observed for TLI (Σ).

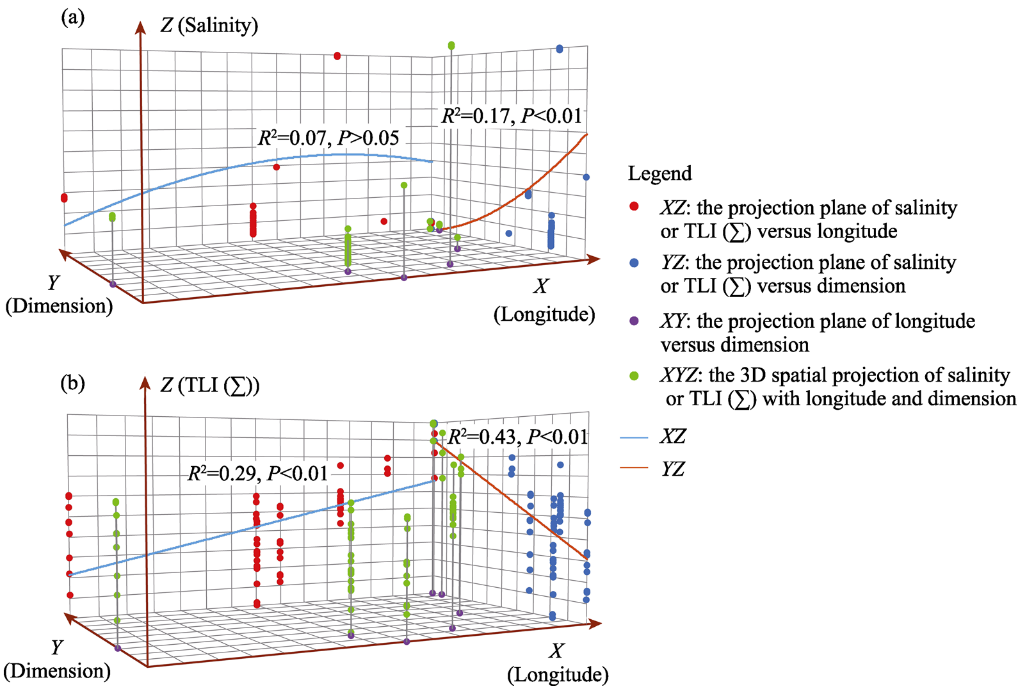

Fig. 4 Spatial trends in salinity (a) and comprehensive trophic level index (TLI (Σ)) (b) of lakes in Inner Mongolia

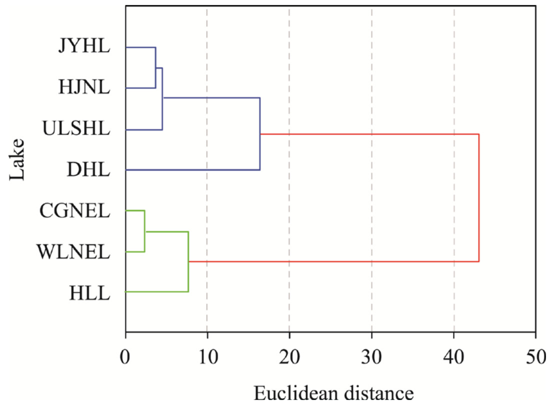

Fig. 5 Dendrogram showing the results of spatial cluster analysis based on salinity and comprehensive trophic level index (TLI (Σ)) of lakes in Inner Mongolia. JYHL, Juyanhai Lake; ULSHL, Ulansuhai Lake; HJNL, Hongjiannao Lake; DHL, Daihai Lake; CGNEL, Chagannaoer Lake; HLL, Hulun Lake; WLNEL, Wulannuoer Lake.

4 Discussion

4.1 Factors driving the spatial variations in lake water quality

Lake water quality is closely related to climate factors, such as precipitation, evaporation, and temperature (Lu et al., 2019; Shalby et al., 2020; Tian et al., 2020), as well as anthropogenic activities (Nyenje et al., 2010; Álvarez et al., 2017; Geng et al., 2021). To explore the possible driving factors of lake water quality, this study analyzed the effects of climate and anthropogenic activities on the spatial variations in lake water quality. Annual mean temperature, annual precipitation, annual sunshine hours, and annual evaporation for each lake were selected as measures of regional climate. Land use is an important carrier for anthropogenic activities, and different land use conditions often reflect the differences in anthropogenic activities (Leon-Munoz et al., 2013; Álvarez et al., 2017). Therefore, the proportion of grassland, the proportion of construction land, and the proportion of arable land in the areas where the seven lakes are located were used as indicators of anthropogenic activities in this study.

4.1.1 Factors driving the spatial differences in the salinity of lakes

Salinity among lakes in Inner Mongolia showed spatial differences, with the salinity of lakes to the west of Daihai Lake (Juyanhai Lake, Ulansuhai Lake, Hongjiannao Lake, and Daihai Lake) higher than that of lakes to the east of Daihai Lake (Chagannaoer Lake, Hulun Lake, and Wulannuoer Lake). The main factors influencing the salinity of lakes during the evolution of inland lakes are the changes of incoming salt loads and lake water levels. Under natural conditions, the transition of an inland lake from freshwater to saltwater is typically gradual over a long period. However, anthropogenic activities in the basin can considerably speed up this transition process (Wang et al., 2015; Liu et al., 2020; Jin et al., 2021). Table 2 shows the correlations of salinity with climate and anthropogenic activities. Salinity was significantly positively correlated with precipitation (r=0.512, P<0.01), and significantly negatively correlated with sunshine hours (r=−0.650, P<0.01) and evaporation (r= −0.326, P<0.01). This was contrary to the influence mechanism of climate on the salinity of lakes under natural conditions, and the reason may be contribute to the influence of anthropogenic activities. In addition, salinity was weak positively correlated with the proportion of construction land and the proportion of arable land. Areas with a large proportion of construction land tend to be densely populated and experience intense anthropogenic construction activity. Socioeconomic development of these areas requires large amounts of freshwater resources. Consequently, a large proportion of freshwater that would normally enter the lake under natural conditions has been intercepted by human demands, resulting in a sharp decrease in lake water recharge and a drop in lake water level, particularly in the western lakes of Inner Mongolia in the arid desert climate region (Wang et al., 2015). The level and area of lakes continuously decreased in the absence of adequate lake water recharge, with the salinity of lakes to the west of Daihai Lake (Juyanhai Lake, Ulansuhai Lake, Hongjiannao Lake, and Daihai Lake) increasing. An additional driver of increasing the salinity of lakes was irrigation return flow, which carries large quantities of salts into lakes along with surface runoff (Liu et al., 2020). While precipitation can act to dilute the salinity of lakes, runoff from precipitation can also carry salts into lakes. Therefore, precipitation can exacerbate lake salinization in areas more affected by anthropogenic construction activity and agricultural cultivation activity. The results of the present study showed that the differences in the intensity of anthropogenic construction activity and agricultural cultivation activity have important influences on the spatial pattern of the salinity of lakes in arid and semi-arid regions, with areas of intense anthropogenic construction activity and agricultural cultivation activity showing higher salinity.

Table 2 Correlations of salinity with climate and anthropogenic activities as well as correlations of TLI (Σ) with climate and anthropogenic activities in lakes in Inner Mongolia

	Temperature	Precipitation	Sunshine hours	Evaporation	Grassland	Construction land	Arable land
Salinity	−0.056	0.512**	−0.650**	−0.326**	−0.398**	0.211	0.148
TLI (Σ)	−0.609**	0.022	−0.376**	−0.369**	0.563**	−0.534**	−0.383**

Note: **, P<0.01 level; TLI (Σ), comprehensive trophic level index.

Correlation analysis among lake water quality parameters showed that salinity was significantly positively correlated with TN (r=0.903, P<0.01), COD_{Mn} (r=0.693, P<0.01), and NH_4^+-N (r=0.460, P<0.01) (Table 3), indicating that the increase in salinity was accompanied by the rises in nitrogen and organic pollutants. In addition, the concentration of nitrogen in lakes in Inner Mongolia was high. Related studies have shown that the abnormal increases in nitrogen concentration of lakes are usually closely correlated with anthropogenic activities (Álvarez et al., 2017; Putt et al., 2019; Tong et al., 2020). The catchment areas of Daihai Lake, Hongjiannao Lake, and Ulansuhai Lake host large human populations and extensive arable land. Therefore, these lakes receive large nutrient loads from human populations, such as domestic wastewater, which directly or indirectly affect lake water quality (Liu and Wang, 2014; Zhang et al., 2019; Zhao et al., 2020). In addition, the excessive fertilization of farmland leads to an accumulation of nitrogen in soil, which can enter lakes through surface runoff and soil erosion caused by

Table 3 Pearson correlation matrix of water quality parameters and TLI (Σ) in lakes in Inner Mongolia

	pH	TDS	Salinity	DO	SD	TP	TN	NH_4^+-N	Chl-a	COD_{Mn}	TLI (Σ)
pH	1.000										
TDS	0.242	1.000									
Salinity	0.233	1.000**	1.000								
DO	0.419**	−0.197	−0.195	1.000							
SD	0.495**	0.251*	0.234	−0.130	1.000						
TP	0.011	0.084	0.092	−0.030	−0.187	1.000					
TN	0.201	0.896**	0.903**	−0.129	0.001	0.210	1.000				
NH_4^+-N	−0.038	0.454**	0.460**	−0.088	0.037	−0.144	0.491**	1.000			
Chl-a	−0.068	−0.324**	−0.326**	0.001	−0.126	0.123	−0.324**	−0.422**	1.000		
COD_{Mn}	0.391**	0.690**	0.693**	0.016	0.213	0.327**	0.706**	0.167	−0.095	1.000	
TLI (Σ)	−0.064	0.095	0.106	−0.023	−0.521**	0.636**	0.312*	−0.208	0.409**	0.408**	1.000

Note: TDS, total dissolved solids; DO, dissolved oxygen; SD, transparency; TP, total phosphorus; TN, total nitrogen; NH_4^+-N, ammonia nitrogen; Chl-a, chlorophyll-a; COD_{Mn}, permanganate index; TLI (Σ), comprehensive trophic level index. *, P<0.05 level; **, P<0.01 level.

precipitation and irrigation drainage (Liu and Wang, 2014; Zhang et al., 2019; Zhao et al., 2020). Therefore, the TN and NH_4^+-N concentrations of Daihai Lake were significantly higher than those of other lakes. The NH_4^+-N concentrations were also generally higher in Hongjiannao Lake and Ulansuhai Lake. These findings indicated that intensive anthropogenic construction activity has resulted in increased salinity, nitrogen concentration, and organic pollutants of lakes.

4.1.2 Factors driving the spatial differences in lake trophic level

Correlation analysis showed that TLI (Σ) was significantly positively correlated with TP (r=0.636, P<0.01), Chl-a (r=0.409, P<0.01), COD_{Mn} (r=0.408, P<0.01), and TN (r=0.312, P<0.05) (Table 3). TLI (Σ) had the highest correlation with TP, indicating that phosphorus was an important indicator of lake eutrophication in Inner Mongolia. Previous studies have shown that eutrophication occurs in nitrogen-limited lakes when the ratio of TN to TP is lower than 14, whereas lake eutrophication is limited by both nitrogen and phosphorus when the ratio of TN to TP is between 14 and 16, and that eutrophication occurs in phosphorus-limited lakes when the ratio of TN to TP is higher than 16 (Collins et al., 2017; Zhu et al., 2022). The ratio of TN to TP in lakes to the west of Daihai Lake (Juyanhai Lake, Ulansuhai Lake, Hongjiannao Lake, and Daihai Lake) in Inner Mongolia ranged from 51 to 140 (Fig. 6), implying that these lakes were in a state of nitrogen excess and lake eutrophication was limited by phosphorus. In contrast, lakes to the east of Daihai Lake (Chagannaoer Lake, Hulun Lake, and Wulannuoer Lake) showed a relatively low ratio of TN to TP, particularly for Hulun Lake and Wulannuoer Lake in which the ratio was lower than 14. The relatively high trophic level of lakes to the east of Daihai Lake (Chagannaoer Lake, Hulun Lake, and Wulannuoer Lake) suggested that phosphorus was the key indicator of lake eutrophication in Inner Mongolia.

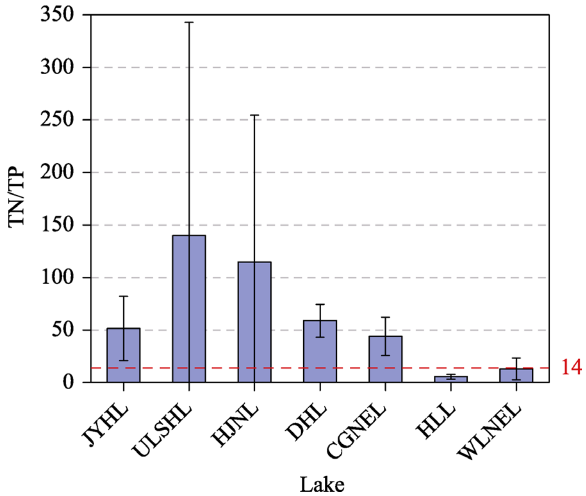

Fig. 6 Ratio of total nitrogen to total phosphorus (TN/TP) in lakes in Inner Mongolia. JYHL, Juyanhai Lake; ULSHL, Ulansuhai Lake; HJNL, Hongjiannao Lake; DHL, Daihai Lake; CGNEL, Chagannaoer Lake; HLL, Hulun Lake; WLNEL, Wulannuoer Lake. The lakes are shown on the x-axis from the left to the right in order of their geographical locations from the west to the east. Bars mean standard deviations.

Higher annual mean temperature and longer annual sunshine hours will promote algal growth, thereby increasing lake eutrophication (Li et al., 2018). However, the results of the present study showed that TLI (Σ) was significantly negatively correlated with annual mean temperature (r= −0.609, P<0.01) and annual sunshine hours (r= −0.376, P<0.01) (Table 2). In addition, TLI (Σ) was significantly positively correlated with the proportion of grassland (r=0.563, P<0.01). The eastern part of Inner Mongolia contains vast grassland areas, such as Xilin Gol grassland and Hulun Buir grassland. These grasslands contain large areas of animal husbandry and overgrazing has led to the degradation of grassland and the disruption of ecological balance. Surface runoff from precipitation has resulted in a loss of grassland nutrients into lakes, with this trend particularly obvious for phosphorus. The accumulation of phosphorus in lakes has resulted in increases in TP concentration and trophic level of lakes from the west to the east (Chen et al., 2012; Yang et al., 2019). Therefore, anthropogenic activities can be regarded as the main factors influencing the spatial pattern of trophic level in lakes in Inner Mongolia. This result is consistent with those of previous studies on lakes in eastern Inner Mongolia (Yang et al., 2019; Wang et al., 2020). However, the results of the present study further showed that grazing intensity was the main factor driving the spatial pattern of lake eutrophication in Inner Mongolia of China, slightly different from those acting on lakes in Mongolia. Shinneman et al. (2009) and Strobel et al. (2021) found that in addition to anthropogenic activities (grazing intensity), climate (warming) is also the main factor driving lake eutrophication in Mongolia. This result further emphasizes the need for focused measures to control lake eutrophication within the different regions of the Mongolian Plateau according to local conditions.

4.2 Overall water quality and eutrophication status of lakes in Inner Mongolia

The lake water in Inner Mongolia can be classified as mainly weakly alkaline overall. In contrast, different lakes showed large differences in TDS and salinity, which could be mainly attributed to the large spatial extent of Inner Mongolia on the longitudinal axis, leading to differences in anthropogenic activities and consequently differences in the salinity of lake water (Wang et al., 2015). The TN and TP concentrations of lake water were found to be relatively high, indicating high levels of nutrient loading in lakes in Inner Mongolia. In addition, COD_{Mn} was significantly positively correlated with TN (r=0.706, P<0.01) and TP (r=0.327, P<0.01) (Table 3), implying that lakes in Inner Mongolia suffered from organic nitrogen and phosphorus pollution. The TLI (Σ) analysis indicated that lakes in Inner Mongolia experienced a certain level of eutrophication. Those results are consistent with the results of previous studies on certain lakes in Inner Mongolia (Liu and Wang, 2014; Yang et al., 2019; Wang et al., 2020). Therefore, there is an urgent need to control the nitrogen and phosphorus loading of lakes in Inner Mongolia. Our study indicated that the concentrations of TN and TP in lakes in Inner Mongolia of China are similar to those in Mongolia (Shinneman et al., 2009) and that most of lakes are eutrophic. This result suggested that lakes of the Mongolian Plateau receive widespread nitrogen and phosphorus pollution. Therefore, more attention should be paid to the prevention and control of lake eutrophication in the future.

Comparisons of the TN and TP concentrations of lakes in Inner Mongolia with those of other lakes in China (Fig. 7) (Zhao et al., 2020) showed that the TN concentrations of lakes in Inner Mongolia exceeded those of other lakes in China, with the TN concentration of Daihai Lake being particularly high. The TP concentrations of lakes in Inner Mongolia were higher than those of lakes in the Qinghai-Tibet Plateau. Except for Wulannuoer Lake and Hulun Lake, the TP concentrations of lakes in Inner Mongolia were similar to those of lakes in the Eastern Plain Lake Region, the Northeastern Plain-Mountain Lake Region, and the Yun-Gui Plateau Lake Region. This result indicated that the TP concentrations of lakes were moderately high in China. The higher concentrations of nitrogen and phosphorus in lakes in Inner Mongolia were closely related to the geographical environment. Inner Mongolia falls within a semi-arid and arid climate zone in northern China, in contrast to the relatively humid Eastern Plain Lake Region, Northeastern Plain-Mountain Lake Region, and Yun-Gui Plateau Lake Region. In addition, Inner Mongolia contains large areas of grassland and arable land, distinct from the Qinghai-Tibet Plateau Lake Region with a lower population. Therefore, human production, living, and overgrazing are the main reasons for the increases in nitrogen and phosphorus loading of lakes in Inner Mongolia (Tao et al., 2015; Zheng et al., 2019). These factors have led to the higher concentrations of nitrogen and phosphorus in lakes of Inner Mongolia than in lakes in other parts of China. These findings support the assertion that different geographical environments explain the regional differences in the nitrogen and phosphorus concentrations of lakes to a large extent (Ding et al., 2015; Li et al., 2018; Tong et al., 2020).

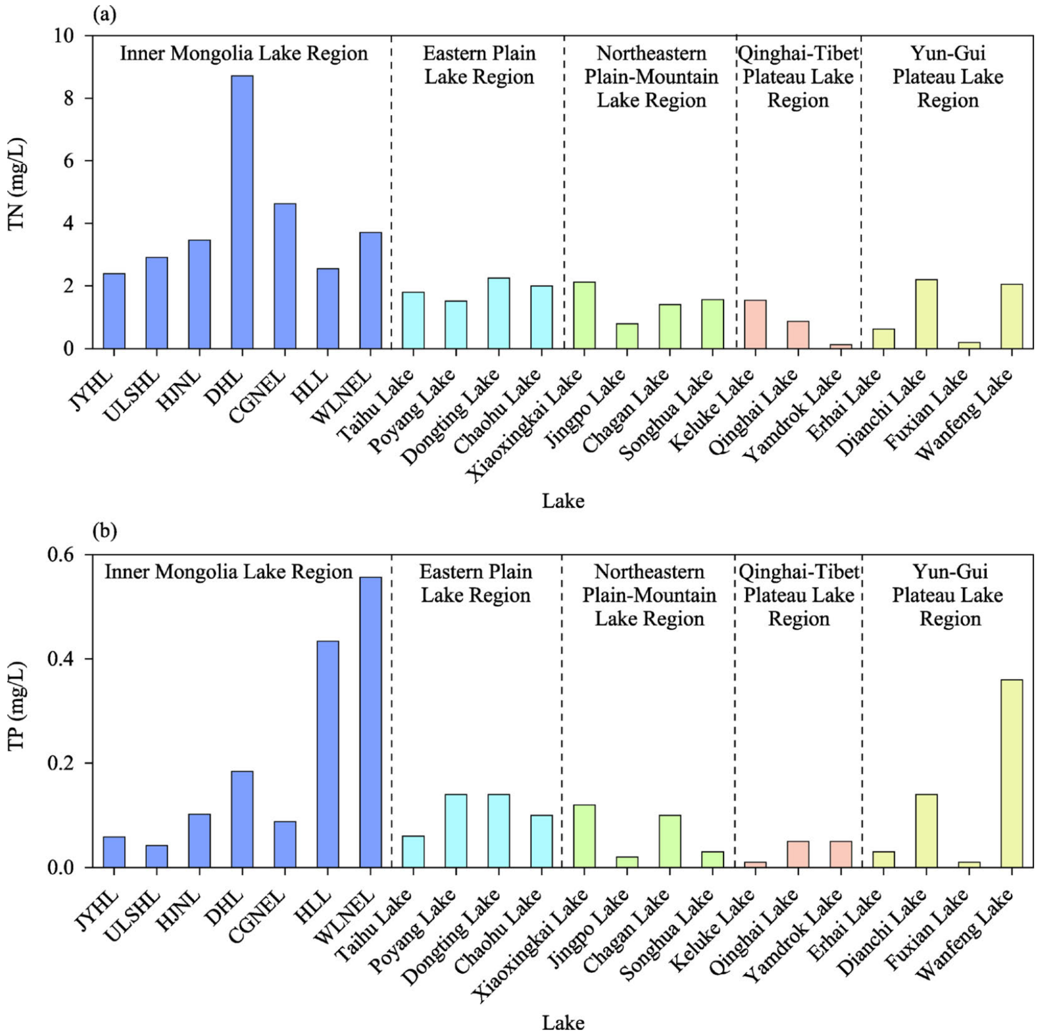

Fig. 7 Comparisons of nutrient concentrations in lakes in Inner Mongolia and in other parts of China. (a), total nitrogen (TN); (b), total phosphorus (TP). JYHL, Juyanhai Lake; ULSHL, Ulansuhai Lake; HJNL, Hongjiannao Lake; DHL, Daihai Lake; CGNEL, Chagannaoer Lake; HLL, Hulun Lake; WLNEL, Wulannuoer Lake.

5 Conclusions

The seven lakes along the longitudinal axis of Inner Mongolia investigated in the present study were weakly alkaline, showing varying degrees of salinization and eutrophication. Nitrogen, phosphorus, and organic pollution were particularly serious, and phosphorus was the dominant indicator of lake eutrophication in Inner Mongolia. The TN concentration in Daihai Lake and the TP concentrations in Wulannuoer Lake and Hulun Lake far exceeded those in other lakes in Inner Mongolia. The water quality of lakes in Inner Mongolia showed obvious spatial variations. Lakes in Inner Mongolia could be divided into two categories in terms of salinity and TLI (Σ): lakes to the west of Daihai Lake (Juyanhai Lake, Ulansuhai Lake, Hongjiannao Lake, and Daihai Lake) and lakes to the east of Daihai Lake (Chagannaoer Lake, Hulun Lake, and Wulannuoer Lake). However, the salinity and trophic level of lakes showed different spatial patterns. The main drivers of lake salinization were anthropogenic construction activity and agricultural cultivation activity, and the salinity levels of lakes to the west of Daihai Lake were higher than those of lakes to the east of Daihai Lake. The trophic levels of lakes were influenced by differences in grazing intensity, resulting in the trophic levels of lakes to the east of Daihai Lake being higher than those of lakes to the west of Daihai Lake.

Future management of lake water quality in Inner Mongolia should strive to adapt to local conditions, control nitrogen and phosphorus loading to lakes, reduce the impact of anthropogenic activities on the lake ecological environment, and strengthen the monitoring of lakes. The findings of the present study can therefore act as a valuable reference for the management of lakes in Inner Mongolia. Although the present study has to some extent addressed the shortage of research on the spatial changes of lake water quality in Inner Mongolia at a large spatial scale, there remains a lack of equivalent research showing the temporal variations. Future research should therefore focus on examining the spatiotemporal changes of lake water quality. This would require the use of long-term monitoring data for evaluating the water quality of lakes in Inner Mongolia. In addition, there is a need for further study on the wide range of factors influencing lake water quality. Future studies on the drivers of changes in lake water quality should examine a wider range of datasets, including geology, soil, groundwater, river water, population distribution, production, and lifestyle.

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