The impact of changed river discharge on water quality deterioration in a prairie lake revealed by the sedimentary evidence

Hongbin Gao, Changyou Li and Biao Sun

ABSTRACT

In order to investigate the historical water quality state and identify the factors causing modern environmental degradation in a prairie lake, total organic carbon (TOC), total nitrogen (TN), stable carbon isotopes of organic matter and total phosphorus (TP) from lake sedimentary core with high resolution age frame were analyzed. The results show that the values of proxies (TOC, TN, TP, $\delta^{13}C$, C/N) increased significantly after 2000 compared with before, which indicates Lake Hulun has heightened nutrient level and pollution extent, thus induced growth of algal bloom and water quality deteriorated after 2000. Since the event of decreased river discharge and lowered water level began in 2000 corresponds extremely well with our sedimentary records that nutrients pollution and eutrophication occurred in Lake Hulun at the same moment, the change of river discharge can be seen as the primary and direct reason of lake water quality deterioration in this period. In addition, the increased wind and water erosion as a result of serious and widespread destruction of grassland in Lake Hulun basin is the potential factors for changing the nutrients concentration in Lake Hulun.

Key words | Lake Hulun, river discharge, sediment, water deterioration

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INTRODUCTION

Lake sediment, as a high-resolution geological archive, has extensive records of past environmental changes (Gierlowski-Kordesch & Kelts 1994). Variations in paleolimnological indicators including physical, chemical and biological proxies in lake sediment provide critical paleolimnological clues about the lake history, including potential interpretation of lake environment, climate and human activities on the regional scale.

Lake Hulun is located in a sparsely populated, agricultural, and industrial steppe area in the northeast part of Inner Mongolia, China (Figure 1(a)). The area has relatively few anthropogenic factors affecting the lake water ecosystem; however, the environment of Lake Hulun has deteriorated and experienced eutrophication with algae blooms in recent years due to the high nutrient concentration in lake water (Li *et al.* 2008). It is important to know the source of nutrient pollutant loading to understand the process of environmental degradation in Lake Hulun. Unfortunately, available data about nutrient levels of surface water, pollutant loading to the lake and human activities in the basin are sparse. Furthermore, because only a few instrumental and documentary records are detailed, it is difficult to identify the changes in lake water quality over a long time-scale and determine whether those changes are induced by anthropogenic activities or natural changes. Paleolimnological reconstruction using the paleoenvironmental proxies archived in the lake sediment have been successfully used to trace the changes of nutrient dynamics and the eutrophication process in lakes and can therefore be used to investigate the history of

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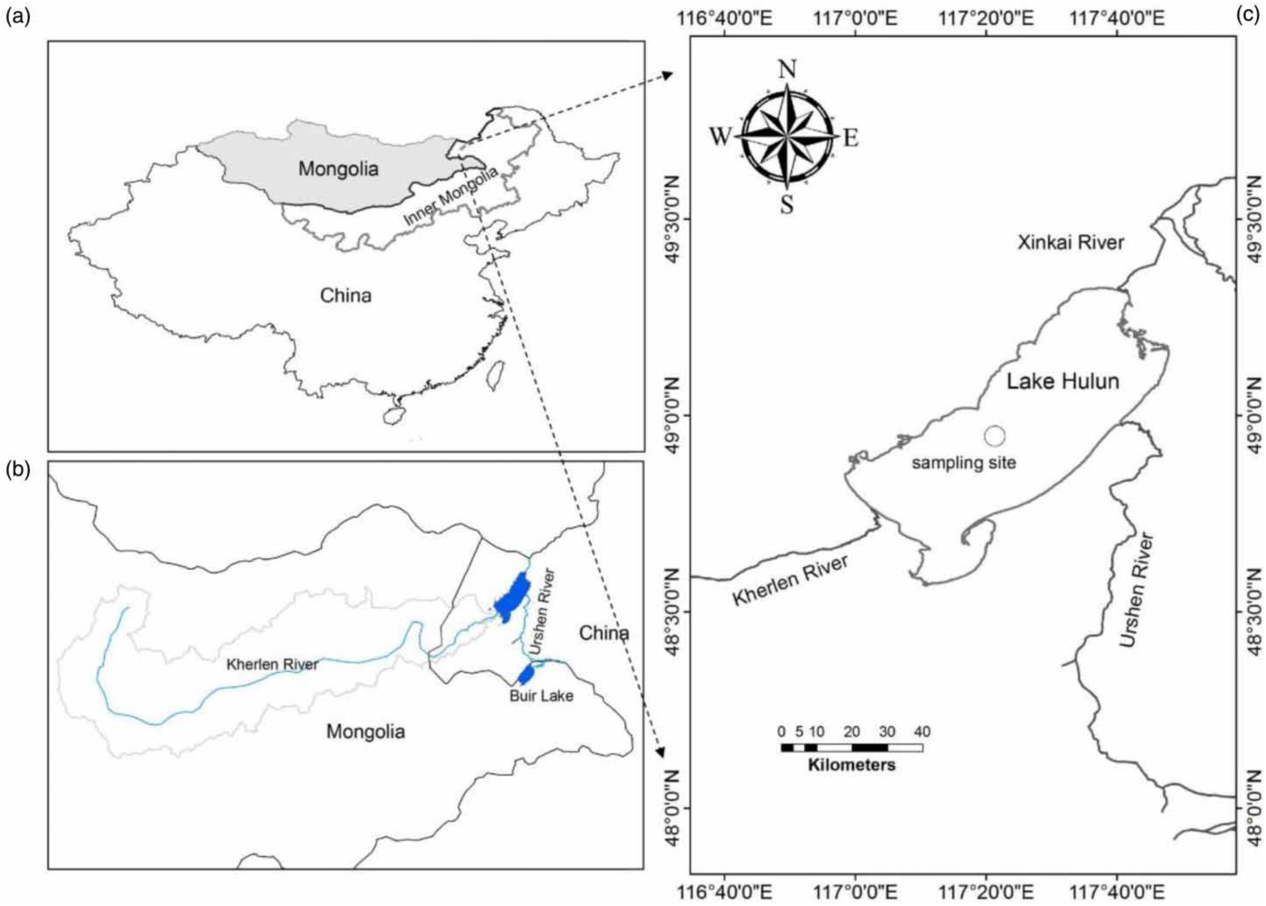

Figure 1 | Location of study area, (a) study area in country scale map; (b) whole Lake Hulun basin and Kherlen river basin; (c) sedimentary core sampling site (black circle).

water quality state of Lake (Brenner *et al.* 1999; Rosenmeier *et al.* 2004; Wang *et al.* 2009). In this study, the measurement of total organic carbon (TOC), total nitrogen (TN), $\delta^{13}C$ and total phosphorus (TP) were conducted in a high resolution dated sediment core. The objective was to trace the change of the water quality state of Lake Hulun in the last 60 years using these proxies for paleolimnological indicators, as well as infer the factors of effect on recent water quality deterioration of Lake Hulun.

METHODS

Study area

Lake Hulun (48°31′–49°20′N, 116°58′–117°48′E), located in a steppe area in the northeast part of Inner Mongolia, China (Figure 1(a)), is the fifth largest lake in China with a maximum surface area of 2,339 km^2 and maximum water depth of 8 m (Xu *et al.* 1989). The basin of Lake Hulun is transboundary between Mongolia and China, of which about 63.7% of the total basin area of 256,000 km^2 belong to Mongolia (Sun *et al.* 2010). In the whole of the lake basin, however, most land areas are covered by the steppe grassland and almost all of the grassland was used for grazing (Onda *et al.* 2007). Two rivers control the main input sources of Lake Hulun, of which Kherlen river basin has about 95% slope runoff yield and concentration are from Mongolia (Sun *et al.* 2010), and Urshen river is derived from Buir Lake (Figure 1(b)). Xinkai river lies north of the lake, is an intermittent river which flows out when lake elevation exceeds 543.4 m.a.s.l. Since the water level declined sharply in the past years, Lake Hulun had become a closed lake without outlet.

Monitoring data of Lake Hulun in the past 10 years (2006–2015) shows that the content of Chlorophyll-a in Lake Hulun ranged from 3.31 mg/m^3 to 10.36 mg/m^3, which is in a relative low level (Liang *et al.* 2016), this phenomenon could be caused by the low air temperature in Lake Hulun basin (mean annual air temperature is 0.3°C) that inhibits the microbial growth process in the lake. In addition, the concentration of dissolved oxygen (DO) ranged from 4.05 to 10.62 mg/L, which is also in a normal level. However, the TN and TP concentrations ranged from 1.7 mg/L to 3.8 mg/L and 0.13 mg/L to 0.25 mg/L (Figure 2), respectively, which have greatly exceeded the National Grade IV Standards of Surface Water. The trophic state index was calculated based on these water quality parameters, which showed Lake Hulun has suffered from eutrophication during this period (Tuan & Xue 2015; Liang *et al.* 2016).

Sampling

A 40-cm-long sedimentary core was obtained at the deepest site with 5.6 m water depth (Figure 1) in Lake Hulun, China, in July 2015 using a Glew Corer (Glew *et al.* 2011). Core samples were sliced immediately in 1 cm intervals on board. Sub-samples were stored in the sealing bags in an ice cooler and then transferred to a refrigerator (<4°C) after being transported to a laboratory.

Experiments and methods

Sediments for carbon, nitrogen, carbon isotopic and TP analyses were ground in a mortar and homogenized. For determining carbon and nitrogen in organic carbon of sub-samples were subsequently treated with 6 M HCl to remove carbonates (Matsumoto *et al.* 2000), then the samples were analyzed using a CN Automatic Elemental Analyzer. For determining TP in lake sediment, dry sediment samples (0.15–0.2 g) was ignited (500°C for 1 h), followed by 1 N HCl and boiled for 15 min on a hot plate, then the dilute extracted solution was measured by a molybdate–antimony–ascorbic spectrophotometer. Carbon isotope (^{13}C) of organic matter was decarbonized with 6 M HCl for 24 h, and the soil–acid mixtures were stirred three times over each 24 h period. Afterwards, the acid was poured off, rinsed with distilled water and stirred the mixtures. The distilled water was replaced every 12 h until the

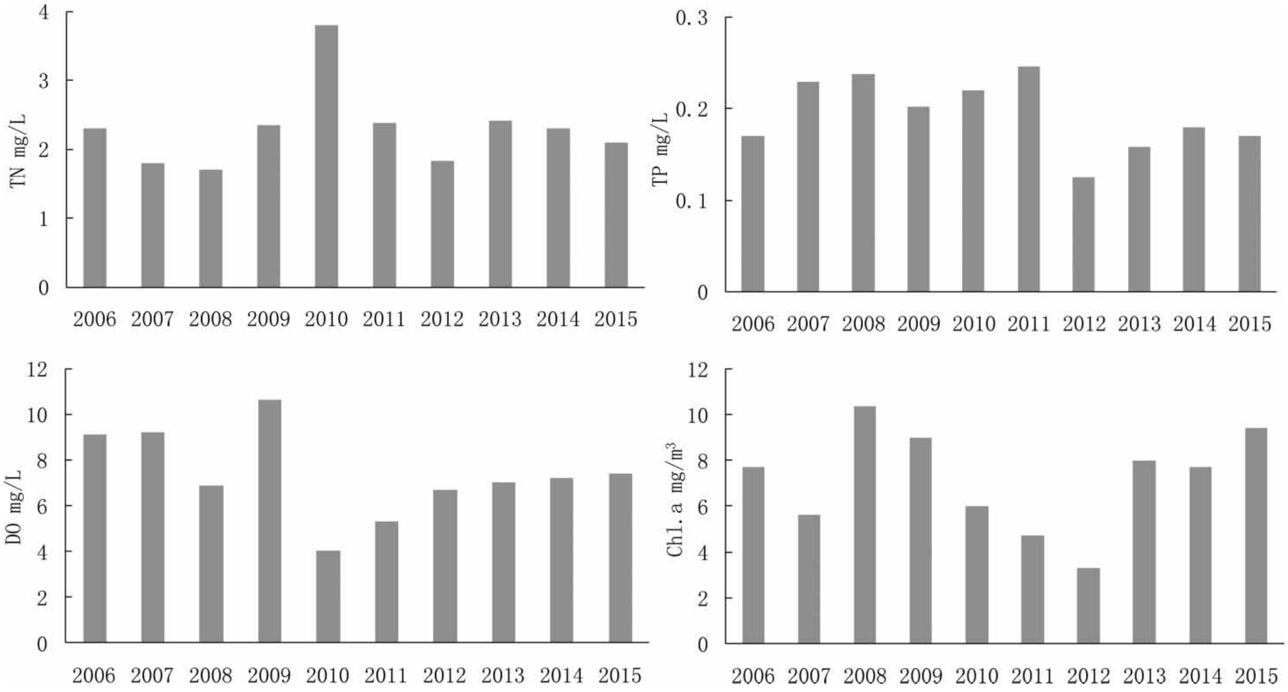

Figure 2 | The concentrations of TN, TP, DO, Chl.a (Chlorophyll-a) in Lake Hulun water in 2006–2015.

soil became dispersed and remained suspended. Soil suspensions were dried at 60 °C in the oven for 12 h, then the soil was ground and analyzed in an isotope ratio mass spectrometer (Midwood & Boutton 1998). Analytical accuracy and precision were compared with known isotopic standards. The analytical precision for standards was within ±0.2‰. The results are expressed innovation as deviations in per mil (‰) differences relative to standard values of international standards (VPDB), shown as below:

$$\delta[‰] = \left[\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1\right] \times 1000$$

RESULTS AND DISCUSSION

Profiles of C%, N%, C/N, δ^{13}C and TP and its interpretation

The analytical results are plotted as profiles with core depth (left y-axis) and sediment ages (right y-axis, unpublished data) in Figure 3. C% and N% in the sediment core show gradual increase trends with variations between 3% and 5% and between 0.2% and 0.4%, respectively. The carbon contents in organic matter during the period between 1960 and 2000 (40–13 cm) varied within a narrow range, while it increased dramatically from 3.82% to 5.07% after 2000 (12 cm–0 cm). The pattern of TN is similar to that of carbon. TP in sediment also has a significant increase at 13 cm, then maintain a relative high concentration at the top of the core. Increased concentration of proxies (TOC, TN, TP) after 2000 indicates Lake Hulun has heightened nutrient level and pollution extent, thus potentially inducing growth of algal bloom and then harm the water quality.

C/N ratios in the core profile varied range from 12.25 to 15.79 with an average value of 14.25, which show higher C/N ratios at the bottom of the core (40–13 cm, 1960–2000), while a significant decrease starts from 12 cm and the lowest C/N ratios occur at the top of the core. δ^{13}C values range from −27.39‰ to – 26.79‰ with an average value of −27.09‰, which decreased during the period prior to 2000 and began to increase around 2000. The maxima in δ^{13}C value is observed around 2010. Changes in carbon isotope abundances of organic matter in the sediment may reflect the variation in lacustrine productivity. The availability of dissolved CO_2 in lake water is a vital factor to control the carbon isotopic composition of phytoplankton organic matter. Because of discriminating against $^{13}CO_2$, phytoplankton preferentially removes lighter ^{12}C from the dissolved CO_2 in epilimnetic waters during photosynthetic uptake (Hodell & Schelske 1998). In addition, lake waters are sensitive to phytoplankton productivity-driven

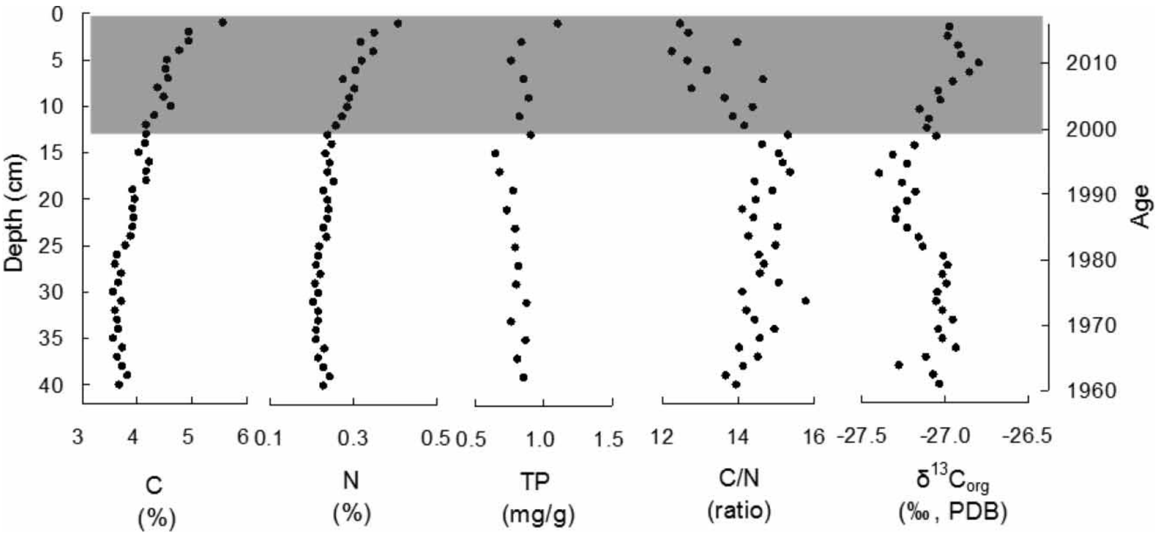

Figure 3 | Profiles of C%, N%, TP, C/N and δ^{13}C of organic matter for 40-cm sediment core from Lake Hulun.

CO_2 depletion due to their limited dissolved inorganic carbon (Meyers 1997), dissolved CO_2 concentration in water can be depleted to near-zero values with ongoing photosynthesis process. As supply of CO_2 becomes depleted and isotopically heavier in water, the discrimination for phytoplankton, therefore, has less against ^{13}C and cause sinking organic matter to be more and more enriched in ^{13}C (Hodell & Schelske 1998). The limited dissolved CO_2 usually occurs during high productivity condition period in lake water, which causes the $\delta^{13}C$ increase in sediment organic matter. Therefore, values of $\delta^{13}C$ can be indicators to identify lacustrine productivity (Hollander *et al.* 1992). Thus, the obvious increase of $\delta^{13}C$ in the sediment core that began in 2000 seems to have been induced by the enhanced productivity in Lake Hulun. This is also proved by the decreasing C/N ratios at the top of the core. Phytoplankton enrich protein and thus have lower C/N ratios than C3 plants, therefore, decreasing C/N ratios can result from high lacustrine productivity (Meyers 1999).

The sediment core records the changes in historical water quality state and degraded processes in Lake Hulun. There are two periods can be separated based on the variation tendency of proxy profiles of sediment. During the years between 1960 and 2000, the sediment depositing had low and relatively narrow range of varied TOC, TN and TP concentrations as well as fairly negative $\delta^{13}C$ values, which are related to low nutrients level and trophic state in Lake Hulun. However, Lake Hulun enhanced nutrients pollution and growth of algae, thus water quality deteriorated after 2000, reflected by the low C/N ratios, high TOC, TN, and TP concentrations, and relatively positive $\delta^{13}C$ values that are stated above.

The factors effect on environmental degradation of Lake Hulun

Nutrient pollution is one of the most widespread and challenging environmental issues in the world, varied nutrient level in aquatic ecosystem usually associate with changes in external sources and its interior. The total discharge from two rivers that flowed into Lake Hulun decreased sharply from 1.75 billion m^3 in 1999 to 0.25 billion m^3 in 2011 caused by decreased precipitation and potential upstream water usage (Figure 4(a) and 4(c)). In combination with the warming and drying of the climate (Figure 4(b)) in Lake Hulun basin, the water levels in Lake Hulun declined above 4 meters from 2000 to 2011 (Figure 4(c)), and the lake has become a closed lake without outlet. As a result, the nutrients in Lake Hulun were greatly inspissated due to lake water evaporation. The water quality investigation for TP and TN in Lake Hulun showed the lake was in a relatively low trophic condition before 2000; however, the lake quality became worse year by year after 2000 (Figure 5). This event is extremely corresponding to our sedimentary records that nutrients pollution and eutrophication occurred in Lake Hulun since 2000, which indicates the reduction of river discharge could be the primary and direct reason of lake water quality deterioration in this period.

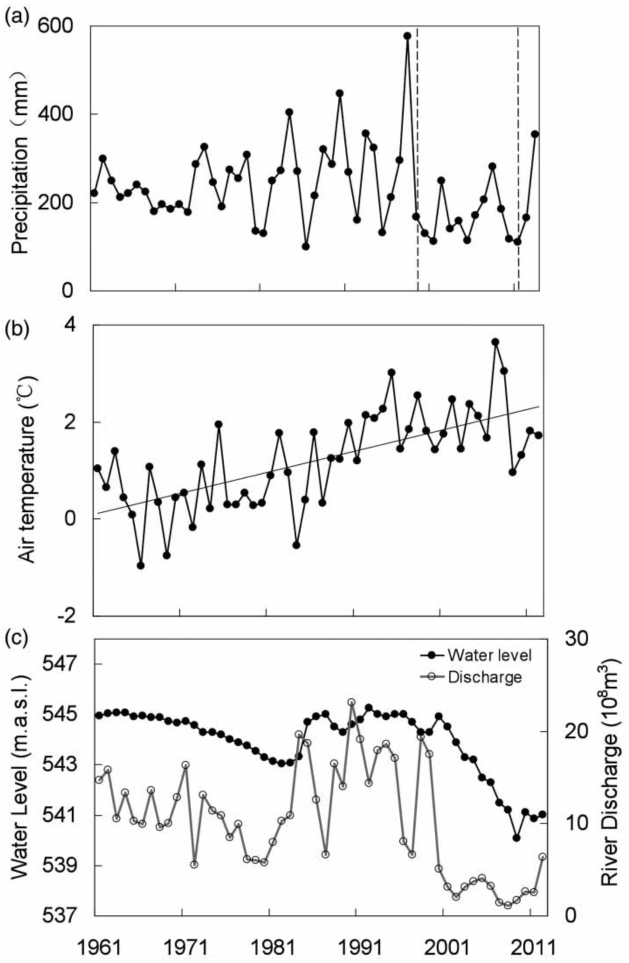

Figure 4 | Variations of annual average precipitation (a), annual average air temperature (b), water level and total river discharge (c) of Lake Hulun in the past 50 years.

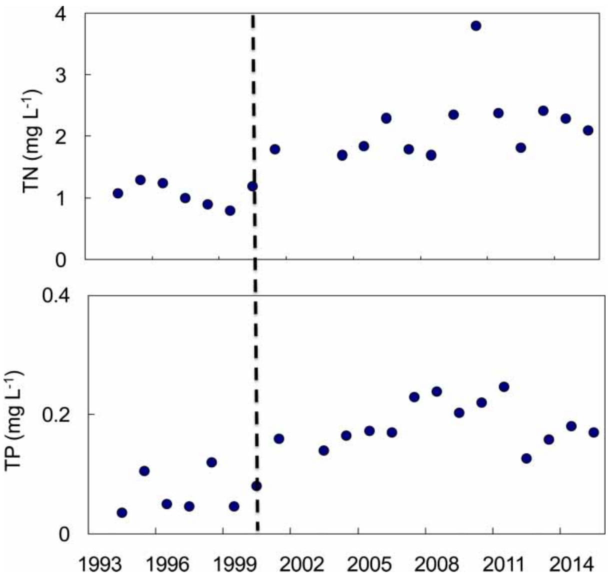

Figure 5 | Variations of TN and TP concentrations (mg /L) in Lake Hulun from 1993 to 2015 (Chuai *et al.* 2012; Liang *et al.* 2016).

Additionally, typically increased land clearing within a watershed can yield a lake response of increasing nutrient loading and productivity because of eroding soils (Cohen 2003). Lake Hulun located in the steppe area with sparse agriculture and industry, organic matters and nutrients are mainly from surrounding grassland (Yan *et al.* 2001), and these are carried into Lake Hulun with input rivers and aeolian dust (soil and hay) by the northwest monsoon (Wang 2006). According to previous investigation, the average concentrations of TN and TP are 1.46 mg/L and 0.12 mg/L in Kherlen River, 1.42 mg/L and 0.09 mg/L in Urshen River, respectively. In combination with the river discharge $4.52 \times 10^8\,m^3$ for Kherlen River, and $5.97 \times 10^8\,m^3$ for Urshen River, the annual total nutrient loading rates can be calculated, which show 1,508 tons for TN and 108 tons for TP input in Lake Hulun every year.

It is well-known that vegetation condition is a primary impact factor on material losses due to wind and water erosion in the arid and semi-arid regions (Lee & Skogerboe 1983; Webb *et al.* 2014). Lake Hulun basin is covered by the wide grassland where most area was used for grazing. Study on Kherlen River basin within Lake Hulun basin (Figure 1(b)) suggested that with the development of the market economy, the number of grazing livestock in the 2000s had doubled since the 1980s and the grazing pressure reached a high level by 0.8 sheep/ha in this area (Onda *et al.* 2007). Furthermore, statistic data from Hulun Buir Bureau showed stronger grazing pressure in part of the lake basin in China was up to 1.7 sheep/ha (Chen *et al.* 2012). However, a number of studies have been conducted on the influence of grazing pressure on soil erosion in grasslands. Evans (1977) found that a critical value of grazing pressure about 0.5–0.6 sheep/ha caused the transformation of a pasture into a desert land. Chen *et al.* (2007) also suggested a proper grazing pressure in Mongolia is unacceptable that exceeds 0.7 sheep/ha. In addition, climate changes also affected the grassland during this period. The annual average air temperature in the basin has increased by 0.05 °C per year (Figure 4(b)), and such warming and drying climate resulted in desertification of grassland. Thus, combined with obvious overgrazing mode and climatic changes over the past few decades led to serious and widespread destruction of grassland in Lake Hulun basin, and further caused the increase of wind and water erosion. Therefore, these are the potential others factors for changing the nutrients concentration in Lake Hulun.

CONCLUSIONS

Our study of the proxies of TOC, TN, TP, C/N ratios, and $\delta^{13}C$ isotopic compositions in Lake Hulun sediment core indicates that low nutrients level and trophic state in Lake Hulun during the years between 1960 and 2000, then the lake enhanced nutrients pollution and growth of algae, and thus lake suffered from eutrophication and water quality deteriorated after 2000. Since the transformed moment of lake environmental state matches well with the event of reduction of river discharge began 2000, the change of water level can be seen as the primary and direct reason of lake water quality deterioration. The results highlight the necessity to consider the management of the river flow and water usage in Lake Hulun basin.

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