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Emerging water pollution in the world's least disturbed lakes on Qinghai-Tibet Plateau

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Abstract: Qinghai-Tibet Plateau (QTP) Lake Region has largest abundance and size distribution of lakes in China. Being relatively away from major human activities, the water quality of these lakes has not attracted concerns in the past. However, dramatic climate change and

intensified anthropogenic activities over the past 30 years have exerted multiple pressures on the water environment of the lakes, resulting in elevated nutrient concentrations in major freshwater lakes of the region. Rapid water quality deterioration and eutrophication of the lakes were first found in Lake Hurleg in the northeast of the plateau. Analyses of driving forces associated with these changes indicate that both the intrinsic characteristics of the QTP lakes and climate change were responsible for the vulnerability to human activities than other lakes in different regions of China, with accelerated urbanization and extensive economic development in the lake basin playing a decisive role in creating water pollution events. Under combination pressures from both natural and anthropogenic effect, the increasing rate of nutrient concentrations in Lake Hurleg has been 53-346 times faster than in Lake Taihu and Lake Dianchi during the deterioration stage. The result suggests the current development mode of Lake Hurleg basin is not suitable for setting protection targets for the QTP lake region more broadly due to its extremely poor environmental carrying capacity. To stop worsening the lake water environment condition, it is necessary to review the achievements made and lessons learned from China's fight against lake pollution and take immediate measures, inform policies into the development mode in the QTP lake region, and avoid irreversible consequences and ensure good water quality in the "Asian Water Tower."

Keywords: Qinghai-Tibet Plateau lakes; water quality decline; anthropogenic activities; climate change; nutrient retention efficiency

Capsule: Decline of water quality occurred in QTP lakes, current regional development mode is unsuitable for the protection of these lakes.

1. Introduction

One-third of lake water in China is stored in 1500 lakes on the vast tectonic region of the Qinghai-Tibet Plateau (QTP) (Wang and Dou, 1998). As essential components of the continental hydrosphere, cryosphere, and atmosphere, the QTP lake region plays a crucial role in water security and ecological stability for the QTP, which was also called "Asian Water Tower" (Lutz et al., 2014). Over the last 50 years, hydrologic processes in the QTP have been substantially affected by climate warming twice to three times faster than the global average (Immerzeel et al., 2010; Li et al., 2014). Due to these temperature increases, the majority of studies in this area have focused on issues associated with the impact of climatic warming on water resources (Yang et al., 2014; Zhang et al., 2013). In contrast, studies on water quality and effects related to environmental stress have been few because anthropogenic disturbance in the QTP has been relatively low in history. Lakes in this area are generally natural, clear, and nutrient-poor (Huang et al., 2009; Mao et al., 2018).

Degradation of aquatic ecosystems caused by climate change and anthropogenic activities permeates globally, from headwaters to oceans, affecting the most sensitive and fragile ecosystems of the earth (Conley et al., 2009; Smith et al., 2003; Smith et al., 2009). Evidence from high altitude arctic regions indicate that increasing temperature and more extensive exploitation of resources has resulted in an increased level of eutrophication (Vadeboncoeur et al., 2003) and brownification (Leech et al., 2018) in lakes. In the QTP lake region, since the 1990s, more than a million nomads have migrated into the area and gained employment in the agricultural, intensive livestock breeding, and tourism industries(Fan Y W, 2012). Significant economic and lifestyle changes in the region have led to a rapid expansion of the anthropogenic pressures, with associated degradation of the environment (Li et al., 2018). Some critical lakes in the Qinghai province, such as Lake Qinghai and Lake Hurleg, have recorded deterioration of water quality and exceeded their protection target(i.e., level II of the China surface water standard) (Ao et al., 2014; Zhou and Yang, 2017).

Lake Hurleg provides essential functions as maintaining ecological biodiversity, water supply for industries and domestic use in the northeast Qaidam Basin. It has also supported the rapid growth of the local economy. Fish farming, tourism, and consumption of water resources have been largely increased since the 2000s, with little attention paid to the water quality. In recent years, a substantial decline in water quality and aquatic community (Fig. S2) has been reported, which implied management and protection measures need to be adopted in terms of preventing loss of ecosystem service functions.

In China, a significant level of investment has been provided for the protection of inland water systems and to combat eutrophication. This action has been presenting promising achievements recently (Tong et al., 2017; Zhou et al., 2017). However, elevated concentrations of water quality parameters like total nitrogen(TN) and total phosphorous(TP) have been identified in lakes that previously had good water quality in the QTP lake region (Tong et al., 2019; Lu et al., 2017). This new situation has resulted in a deviation from the original aim of the national lakes protection policy.

To investigate nitrogen(N) and phosphorus(P) pollution and to protect lakes in the QTP, we will initially collect data and present the variation of nutrient concentration in QTP lakes, focusing on Lake Hurleg. We will then explore the leading causes of water quality decline, examining the key challenges affecting the protection of QTP lakes. Finally, we will review lessons learned from the past water pollution mitigation practices and inform the protection strategies for the QTP lake region.

2. Materials and methods

2.1 Study area

The QTP lake region is situated between 26°00′ to 39°46′N and 73°18′ to 104°46′ E with an altitude range of 2700 to 5000 m a.s.l.. In this region, 87% of lakes are classified as being saltwater lakes. However, the freshwater lakes, which have a total storage capacity of 693.42×10^8 m^3, provide a critical source for society and ecosystems.

Lake Hurleg (37°17'N, 96°54'E; 2817 m.a.s.l.) is the largest endorheic freshwater lake in the Qaidam Basin of Qinghai Province, situated at the northeast of the QTP (Fig. 1a). The geomorphology of the Lake basin is made up of the valley and alpine desert type rangeland, the overall terrain presents the characteristics of high in the north and low in the south, the northern mountains are the Zongbolong Mountain with an elevation above 4000 m. It is the main source of water in the basin. In front of the steep southern slope of the mountain with intense erosion is the floodplain. Lake Hurleg and Lake Toso are located at the center of the east-west sedimentary belt south to the floodplain. The Bayin River (1.9×10^8 m^3/year, obtained from local authorities) and the Balegen River (0.1×10^8 m^3/year)cut the mountain from the north and flow into Lake Hurleg. (Fig. 1b) Lake Hurleg has a surface area of 58.03 km^2 and a lake volume of about 2×10^8 m^3, the maximum water depth (9.6 m). Lake water flows out through a small stream that discharges into Toson Lake. The mean residence time of water in Lake Hurleg is about 1 year (Zhao et al., 2010). The Lake basin has a westerly influenced dry continental climate(Tian et al., 2003). Its mean annual precipitation of ~160 mm, and its mean annual potential evaporation is ~2000 mm. The lake basin is dominated by desert vegetation and lack of high-quality pastures; most of the pastures are concentrated around the lake.

2.2 Sample determination and data preparation

2.2.1 Sample collection and measurement

Field sampling in Lake Hurleg basin was carried out in the summer of 2017. Samples were collected at 20 sites, including three sites along Bayin river(N1~N3) and 17 sites distributed in Lake Hurleg(small panel in Fig. 1b) at a depth of 0.5m. Samples were collected in pre-cleaned, acid-washed, brown polyethylene bottles, and stored at 4 °C before laboratory analysis. TN, ammonia nitrogen (NH_3-N), total phosphorus (TP), chemical oxygen demand(COD_{Cr}) were in the laboratory using the standard methods (APHA, 2005).

Samples for dissolved organic carbon (DOC) and Three-dimensional Excitation Emission Matrix Spectra (3D-EEMs) analysis were filtered with pre-combusted GF/F 0.7 mm filters (Whatman). Then DOC concentration was measured in a TOC analyzer (Shimadzu TOC-VCSH) using a non-purgeable organic carbon method. The EEMs fluorescence of dissolved organic matter(DOM) was measured by Hitachi F-7000 fluorescence spectrometer (Tokyo, Japan) with a 700-voltage xenon lamp at room temperature (20 ± 2° C). All samples were diluted to minimize the inner-filtering effects(Ohno, 2002). The scanning ranges were 200-450 nm for excitation and 250-600 nm for emission. The scanning was at 5 nm intervals for the excitation/ emission wavelength by using a scanning speed of 2400 nm/min. The EEMs for all samples were blank corrected and converted to Raman Unit (R.U.) (Mangalgiri et al., 2017). For the identification of DOM sources, the EEM spectra are divided into five regions,i.e., I-IV according to Chen et al. (2003), which regions I, II and IV are considered to belong to protein-like materials and phenolic compounds while regions III and V are associated with fulvic- and humic-like substances. Besides, two widely applicated fluorescence indices, fluorescence index(FI) and humification index (HIX), were utilized. (McKnight et al., 2001; Huguet et al., 2009; Korak et al., 2014).

2.2.2 Water nutrient data

Water survey data of TN and TP from 3 lakes(Lake Qinghai, Lake Zhaling, and Lake Erling) in the QTP lake region between 1988~1992 (1990s) were obtained from the Lake-Basin Science Data Center, National Earth System Science Data Sharing Infrastructure, National Science & Technology Infrastructure of China (http://lake.geodata.cn). TN and TP data of QTP lakes spanning 2010~2016 (2010s) were recorded from related studies in the region (Lin et al., 2017; Lu et al., 2017; Yang et al., 2018; Yan et al., 2018), all samples were collected during the summer period. Water quality data for Lake Hurleg (2003~2016) was obtained from the local administrative sources.

To better reflect the changes in nitrogen and phosphorus concentrations in QTP lakes, we further selected TN and TP concentration data from the other four lakes for comparison. We compiled water quality parameters(TN and TP) by searching the China National Knowledge Infrastructure (http://www.cnki.net) and ISI Web of Science (http://apps.isiknowledge.com) following the method of Liu et al. (2010). A total of 122 lakes & reservoirs (80 in the ECP(East China plain lake region), 18 in the YGP(Yunnan-Guizhou Lake Region), 11 in the IMX(Inner Mongolia-Xinjiang lake region), and 11 in the NEC (Northeast China plain lake region)) were collected for comparison. As it was not possible to collect nutrient parameters for all lakes within the same year, the collected data of each lake region were grouped in 2 periods with 5 years, i.e., 1990s (1990~1995) and 2010s (2010~2015). To minimize the among-year error, the mean value of each lake is utilized in the analyses.

2.2.3 Data of human activities in the lake basin

For comparison of sensitivity among lakes with different levels of human activities, two shallow lakes with extensive research during the eutrophication were chosen, Lake Taihu from the economic and prosperous ECP lake region, Lake Dianchi from the developing YGP lake region. Data on economic and social development in the lake basin Taihu, Dianchi, and Hurleg, including the population, the rate of urbanization, the (GDP), the production of agriculture, livestock breeding, and fish farming was obtained from statistical yearbooks of major cities in each basin.

2.4 Data analysis

2.4.1 Nutrient removal efficiency calculation

To compare the influences on nutrient input with different morphology across lake basins, we calculated lake nutrient removal efficiency as a metric.

Finlay et al. (2013) defined the nitrogen removal efficiency (NRE) of a lake as 1-N_{out}/N_{in}, i.e., the proportion of the annual total nitrogen input that is retained by the lake. In our study, we use this definition as nitrogen retention efficiency (NRE_{lake}), the NRE_{lake} is calculated as:

$$\mathrm{NRE}_{lake} = a * Log_{\tau} + b \qquad (1)$$

Where, NRE_{lake} is the N retention efficiency in lakes of varying trophic states; τ is the water residence time (WRT; years); a is the slope of the relationship (0.22±0.05 for mesotrophic lakes and 0.23±0.02 for eutrophic lakes), and b is the intercept (0.57±0.06 for mesotrophic lakes and 0.54±0.02 for eutrophic lakes), the slope and intercept were calculated by Finlay et al. (2013, Tab S2).

In our study, TP retention efficiency (PRE) was defined as TP_{in}/TP_{lake}, i.e., the relationship between the inflow and outflow proportion of annual total phosphorus input of P retained by the lake. Brett & Benjamin (2008) tested the hypothesis related to lake phosphorous retention and found that the PRE was best fitted as:

$$TP_{lake} = \frac{TP_{in}}{1 + k\tau_w^x} \tag{2}$$

Where TP_{lake} is the P retention efficiency of various trophic lakes; τ_w is the water residence time (WRT; years); k and x are constants (k=1.12±0.08 year$^{-0.47}$; x=-0.53±0.03).

so we calculated the PRE_{lake} as

$$\text{PRE}_{lake} = \frac{TP_{in}}{TP_{lake}} = 1 + k\tau_w^x \tag{3}$$

2.4.2 Parametric model of the Environmental Kuntz Curve(EKC model) with NRE/PRE and environmental vulnerability

An important aim of our study was to access the response of water quality in QTP lake to human activities. The human footprint has been a suitable measure to indicate direct human influence on ecosystems (Sanderson et al., 2002). However, existing studies considering the human footprint in the QTP region are insufficient(Fan et al., 2015; Yi et al., 2020).

Therefore, we utilized a modified EKC model because the gross domestic product (GDP) provides a measure of economic development and environmental quality that can be explored. Typically, a general reduced-form model comprising a quadratic or cubic function of income and a linear function of other factors that affect environmental quality are used to test the Environmental Kuntz Curve (EKC) hypothesis (Grossman and Krueger, 1995; Dinda, 2004). In our study, to reflect the difference in buffering capacity introduced by variations in morphological characteristics and local environmental conditions among lake basins, we modified the input variable to take account of nutrient retention efficiency and provincial environment vulnerability(E_i), which is based on the entropy method and accessed following the method of Zhao et al. (2018). Modified GDP was calculated as:

$$\mathrm{GDP}_{Mod} = \mathrm{GDP}_{origin} * NRE_{lake}(PRE_{lake}) * E_i \quad (4)$$

where, GDP_{Mod} is the modified economy density (10^4 yuan/km^2); GDP_{origin} is the original economy density from the data collection; $NRE(PRE)$ is nutrient retention efficiency; and E_i is environmental vulnerability.

The EKC regression was:

$$WP_i = \beta_0 + \beta_1 X_{it} + {}_2 X_{it}{}^2 + \beta_3 X_{it}{}^3 + \varepsilon_{it} \quad (5)$$

where WPi is water quality indicator; X_{it} is log-transformed GDP_{Mod}; ε_{it} is the error term; β_0, β_1, β_2, β_3 are the estimated coefficients.

2.5 Statistical analysis

Statistical analyses, including the calculation of mean values, standard deviation, t-test, and linear correlations were undertaken using Origin 2018 software. The spatial distribution of water quality-related parameters was determined using ArcGIS 10.2. Linear fitting and t-test results with $p < 0.05$ are reported as significant. Means are given with plus/minus their standard deviations.

3. Results

3.1 Variations of nutrient concentrations in QTP lakes

Over the last 30 years, median total nitrogen (TN) concentrations in the QTP lakes increased from 0.49 $\pm$ 0.22 mg/L in 1985~1990 (median 0.49 mg/L, range of 0.15~0.76 mg/L, interquartile range (IQR)=0.44 mg/L, n = 6) to 1.27 $\pm$ 2.11 mg/L in 2010~2016 (range of 0.03~12.77 mg/L, IQR=0.79 mg/L, n=40). The rate of increase of TN concentrations was significant(p=0.01) and greater than the rate of expansion of lake surface area in the QTP lake region (Fig. 2a) (Mao et al., 2018). Wen et al. (2019) reported a higher and likely dispersed TN concentration of 3.79 $\pm$ 4.46 mg/L during the investigation of DOC in Tibetan lakes (range of 0.18~25.67 mg/L, n=310). The maximum value was from saline lakes. In 2010~2016, TN concentrations in 14 of the lakes were higher than the Level II water quality standard of China (0.5 mg/L).

Results for TP concentrations over the same periods did not record a significant trend(p=0.13), the median value recorded a slight increase from 0.024 $\pm$ 0.01 mg/L in 1985~1993 (median 0.02 mg/L, range of 0.014~0.041 mg/L, IQR=12.33 μg/L, n = 5) to 0.051 $\pm$ 0.098 mg/L in

2010~2015 (median 0.17 mg/L, range of 0.002~0.65 mg/L, IQR=0.027 mg/L, n = 76) (Fig. 2a), while Wen et al. (2019) also obtained a concentration of 0.13±0.32 mg/L(n=310), which is two times of our value, suggested that our results may underestimate the nutrient concentration in QTP. According to our study, in 2010~2015, TP concentrations in 14 lakes were higher than the Level II China surface water standard and 7 exceeded the eutrophication threshold set by OECD (>35 μg/L) (OECD, 1982).

The coefficients of variation (CV) results for TN and TP recorded the most significant variation occurring in the QTP lake region, although average TN and TP concentrations in the QTP lakes are still the lowest across all lake regions of China. The CV of TN and TP from the 1990s to 2010s increased by 20% and 271%, respectively. With being ranked top in all lake regions (Fig. 2b). In contrast, CV for TP during the same periods declined by 50% in the ECP and the NEM regions while in the IMX region recorded a slight increase, and CV in the YGP region remain steady. In contrast to TP, the TN CV results in China lakes recorded a more consistent trend, with only the QTP and YGP regions recording an increase of more than 5%; trends in the NEM and ECP regions were insignificant. Although these results indicate that differentiation in TP concentrations was more obvious than TN, they also implied the rapid accumulation of TP in some QTP lake basins in the last three decades.

TN and TP concertation trends in Tibet and Qinghai (Fig. 2c~d) were divergent. TN concentrations in three Tibetan lakes (Nam Co, Yadrok Co, and Pomo Co) recorded gradual increases, whereas that of the two lakes (Lake Zhaling and Lake Eling) in Qinghai generally remained stable. In contrast, TN concentrations in Lake Hurleg and Lake Qinghai rose more steeply than those of the other six lakes. Overall, Lake Hurleg recorded the fasted increase, reaching 83.4%/10a.

In terms of TP concentration, two lakes in Tibet (Nam Co and Yadrok Co) recorded a decline, with a drop of 19%/10a, while those of Pumo Co increased by 20%. In Qinghai, three out of four lakes recorded an increase (Lake Hurleg recorded the highest rate of increase with 60.6%/10a) and only Lake Zaling recorded a slight decrease. Notably, lakes in the Qinghai province had a greater contribution to the variation of nutrient concentrations in the QTP lake region.

3.2 Trends of water quality variation in Lake Hurleg

Over the past ten years, water quality in Lake Hurleg undergone a marked deterioration. The main water quality parameter changed abruptly after a massive flood in 2013. TN, TP, and Chemical Oxygen Demand(COD_{Cr}) concentrations increased by 516%, 433%, and 244% over three years (Fig. 3a~b). In the meantime, transparency(SD) decreased by 18.87%. Between 2012 and 2015, the trophic State Index (TSI index) of

Lake Hurleg increased by 61.2% (29.9 to 48.2), which indicated a rapid improvement of eutrophication.

Variation of water quality sampling along the Bayin river in 2017 was shown in Fig. 3c and Tab S1. indicated that COD_{Cr}, NH_3-N, TN and TP concentrations upstream waters (N1) were 22.00 ± 1.10 mg/L, 1.42 ± 0.04 mg/L and 0.026 ± 0.003 mg/L, respectively. After mixing with the city municipal sewage effluent(Standard A of Level I in China, Table S3) and In the agricultural runoff canal of from wolfberry farm (N2), COD_{Cr}, NH_3-N, TN and TP concentrations increased to 62.19 ±3.55 mg/L, 0.15 ± 0.04 mg/L, 3.4 ± 0.13 mg/L, and 0.026 ± 0.003 mg/L, respectively, attaining the highest levels in the basin. The highest ammoniacal nitrogen (0.48±0.03 mg/L) was recorded in the pasture area (N3) near the eastern lakeshore, coinciding with the activity patterns of livestock herds. It is estimated by authorities that more than half the local livestock (240k sheep, 24k large domestic animal in total) are grazing in these pasture during the summer. Finally, lake water reflected the mixed characteristics of pollution from agriculture and animal husbandry, where the COD_{Cr}, TN, TP, and NH_3-N was 22.05 ± 4.20 mg/L, 1.25 ± 0.14 mg/L, 0.022 ± 0.004 mg/L, and 0.41± 0.14 mg/L, which have exceeded level III of water quality standards for surface waters in China.

Variation of DOM content and its fluorescence properties in the basin were characterized by DOC and 3D-EEMs Spectra. The concentration of

DOC significant increased(81%) from upstream(N1) to lake(N4). The spectra from N1 presented the peaks in region I and IV, which are typically associated with protein-like materials. This spectra of microbially-derived DOM has also been found in other remote and pristine freshwater in the alpine lakes (Mladenov et al., 2011). From the wolfberry runoff(N2), allochthonous sourced DOM appeared as the peak intensity in the longer emission wavelength increased in region III and V(Fig. 3b), associated with the fluvic- and humic- substances. After flow into the mainstream, the FI decreased from 1.9(N1) to 1.58(N3) in the lakeshore, while HIX increased from 0.34(N1) to 0.88(N3). The fluorescence indices of Lake Hurleg water(Fig. 3d) were inclined to terrestrial source FI(1.45), Consistent with the trends of water quality parameters, indicate substantial terrestrial input.

In summary, the variation in water quality and optical character of DOM provide essential information that primary pollution sources of Lake Hurleg were livestock leach from lakeside pasture and soil organic matter laden agricultural runoff water from reclaimed wolfberry farmland in the surrounding wetlands.

3.3 Nutrient removal retention in the QTP lake region

As detailed in the Methods section, mean water residence time (τ·years) was a critical determinant of nutrient retention efficiency

(NRE/PRE). In China, three terrain areas, ascribed as the first terrain ladder (FTL), second terrain ladder (STL), and the third terrain ladder (TTL). The elevation difference of 2000 meters between each terrain ladder led to significant differences in climate and basin morphology of lakes on the different ladder. which are essential in controlling nutrient input and water quality. (Nõges et al., 2009; Liu et al., 2010). Ranges of NRE and PRE of lakes from three terrain areas have significant differences (Fig. 4 and Table S7). The FTL lakes have the highest average retention efficiency. The PRE is 10%-148% higher than STL and TTL lakes, while NRE is 11%-122% higher. The slower water circulation rates and lower biological transformation resulted in nutrients primarily accumulating in FTL lakes, indicating that water quality in the QTP lake region will generally be more sensitive to an increase in water pollution intensity than lakes in other regions.

3.4 Relationships between water quality and GDP growth rate in QTP lakes

In Lake Taihu and Lake Dianchi, EKC regression presented that variation in concentrations of TN and TP was significantly associated with GDP, the inverse U curve also indicated the relationship between water quality and GDP fitted well with the EKC model in Lake Taihu and Lake Dianchi, while the turning point still not observed in Lake Hulrg basin,

(Fig. 5) Suggest that the concentration of TN and TP in Lake Hurleg would rise when the economy continues to develop.

To access the response of water quality in QTP lakes to human activities, the GDP growth rate was utilized in the study. It was defined as the increase of GDP in the lake basin when the initial nutrient concentration in the lake increased by 100% during the water quality degradation phase. In Lake Taihu basin, the ratio of GDP growth rate to TN and TP concentrations was 2.51×10^7 and 7.0×10^7 yuan/km^2, respectively. Around Lake Dianchi, growth rates were 5.33×10^7 and 1.18×10^7 yuan/km^2, respectively. In Lake Hurleg, the curve is still rising, and the turning point has not yet been observed. Nevertheless, GDP growth rates at this site declined to 1.54×10^4 and 2.21×10^5 yuan/km^2, respectively, indicating that the nutrient concentration in the lake has responded 163 times (TN) and 317 times (TP) faster than that in Lake Taihu in terms of the economic development level in the lake basin, and 346 times (TN) and 53 times (TP) faster than that in Lake Dianchi.

4 Discussion

To date, the water quality survey in the QTP lake region was limited, our analysis of available data provides an insight into adverse trends in this area over the last three decades. Our study of Lake Hurleg also revealed the emergence of a rapid decline in water quality in this region, which is firstly recorded in the QTP Lake region and beyond normal experience and expectation. Although water pollution in the QTP lake region is localized and in an initial stage of polluting water sources, significant differences in the variation of TN and TP concentrations compared to other lake regions suggest that environmental pressures are accelerating in the region.

4.1 Drivers of water quality decline in QTP lake region

In the past four decades, anthropogenic activities had significantly impacted Chinese inland waters. The unrestricted industrial and domestic wastewater discharge and fish farming exacerbated the deterioration of lakes in the ECP lake region since the 1970s and reached the worst level in 2000s (Le et al., 2010). Following the eastern lakes, in IMX Lake Region and YGP Lake Region underwent a drastic water quality decline with the prosperity of mining, agriculture, and unrestricted drawing from lakes (Tao et al., 2011; Liu et al., 2012).

In the QTP lake region, however, the water quality deterioration processes have been more inclined to be induced by a combination of natural and anthropogenic factors and thus bear a greater risk of developing a traditional economy. Due to the region's rich mineral resources, most industries on Tibetan Plateau are resource-based industries with high water consumption. An increase in industrial and residential water consumption has reduced the amount of water available to support the ecology of lakes, farmlands, and wetlands. When farmers and herders focused on increasing their income, the mode of agricultural production and livestock breeding has rapidly changed. In Lake Hurlg basin, between 2012 and 2017, areas planted for cash crops, with receiving high fertilization, increased by 40.36%, and the production of meat and aquatic products has increased by 71% and 100%, respectively. Then the development of traditional livestock farming and agriculture is very easy to fall into a downward spiral of overgrazing and desertification, resulted in an increase in erosion and direct nutrient loss into the river, as determined by our result along Bayin river. Studies examining unstrained/heavy intensity grazing have also concluded that animal waste has significantly contributed to pollution enrichment in water bodies adjacent to pasture areas (Belsky et al., 1999; Hooda et al., 2000; James et al., 2007). Finally, the excessive development of fish farming in this area has also resulted in a decline in macrophytes due to high fish populations and a reduction in the self-resilience of the aquatic ecosystems.

Concurrently, climate change has resulted in an increase in the frequency of extreme weather events, which have amplified the loading of nutrients and organic matter into water bodies, ultimately decreasing water quality. This "double whammy" effect driven by climate change and intensified anthropogenic activities have significantly impacted the nutrient concentration in QTP lakes. Additionally, the unique geographical features and fragile environment of the QTP lakes mean that they are likely to be even more strongly affected. The same history has also been reported in a basin located in the subarctic zones of Canada (Schindler et al., 2012) and the semi-arid regions in China (Chen et al., 2012).

4.2 Elevated environmental pressures in the QTP lake region

4.3.1 Elevated nutrient release induced by climate warming

In recent decades, large-scale thawing of permafrost is accelerating (Wu et al., 2013; Wang et al., 2019). This thawing of the permafrost layer could cause a substantial loss of activated nutrients over the permafrost zone of the QTP due to stimulated decomposition and mineralization of organic nutrients (Zhao et al., 2018). The loss of C and N mostly occurs in the active layer and positively correlated with active layer thickness(ALT)(Harms & Jones, 2012; Salmon et al., 2016). During the period of our study, a significant increase of active layer thickness(ALT) in 93.8%(15/16) monitoring sites on QTP has been confirmed(Luo et al., 2016). Other in-situ investigations have given the facts that solid coupled carbonous and nitrogenous substances enriched in the topsoil of QTP by 24% compared with 1980s, while DIN and DON content are 67.5% and 594% higher than in permafrost, respectively. (Tian et al., 2019; Mao et al., 2020). DOC export rate was estimated to range from 0.26 to 0.912 g C $m^{-2}yr^{-1}$ in QTP(Ma et al., 2019). It is predicted that the area of permafrost in this region will decrease by 58% by 2089 (Yu et al., 2012). Under such circumstances, 2~3% (~5 × 10^7 t) of nitrogen and carbon will be lost to air and water along various pathways(Zhao., 2018).

The export of C and N are closely related to basin hydrology. In addition to the release by permafrost thawing, an increase in rainfall fluctuations induced by climate change has also exacerbated erosion in the QTP region and contributed to elevated riverine export of nutrient. (Wang et al., 2007; Wang et al., 2008). Take northeast QTP for example, since the 1960s, annual rainfall erosivity tendency has escalated by 270% in the Qaidam Basin and northeastern areas of the QTP (Kang et al., 2017; Liu et al., 2013). As these areas are covered with fragile and low-buffer capacity sparse alpine steppe and meadow vegetation, the concentration of rainfall in summer (80% of annual rainfall) has resulted in severe soil erosion in these regions.

Consequently, as received organic substance from river, streams, and groundwater, lakes ecosystem in this region have been affected. These organic substances include ancient DOM fuel the bacteria-plankton food web in the QTP lakes, which no inhibition with increased salinity. (Spencer et al., 2015; Yang et al., 2020; Hu et al., 2016). Taken collectively, these evidence are believed to demonstrate that permafrost thaw and hydraulic erosion caused by climate change are responsible for releasing large amounts of bioavailable C and N in QTP lakes, resulting in elevated background nutrient concentrations and variations in ecological and water quality. (Harms & Jones, 2012; Wickland et al., 2018; Salmon et al., 2016). Overall estimation of exported C and N in QTP is unavailable at this time, while such research is growing(Ma et al., 2019).

Moreover, further study involving the currently poor understood phosphorus dynamics under climate change in the QTP lake region is also needed because it is a more desired nutrient for the aquatic ecosystem than N and C in high mountain pristine lakes, with could significantly affect the trophic status and water quality with a subtle increase in the supplies(Elser et al., 2007, Harpole et al., 2011).

4.3.2 Intensified anthropogenic pressures in the QTP lake region

Over the last 30 years, significant achievements have been made in the QTP in terms of economic growth and improvements in people's welfare. The total GDP of Qinghai and Tibet has grown by 130 times, along with population growth and an increase in animal husbandry by 55%; fertilizer intensity has increased by 250%. Since 1992, tourist numbers have increased by 1600 times, reaching 36.69 million in 2016 (Fig. 4a). The tourism consumes and discharges as much as the whole urban population in Tibet and 30% of the urban population in Qinghai every year. Largely intensified human activities have contributed to an increase in regional pollution. It has been calculated that total COD, TN, and TP discharge to the environment on the plateau in 2016 was 1.15~2.72 times greater than discharge in 1990 on average(Table S4). In 2018, the economic growth of the QTP region continued to accelerate, and anthropogenic pressures on the QTP lake region will likely keep the pace of rapidly increasing.

Besides, there is another key finding that the diverging TN and TP concentrations in lakes in the QTP region were consistent with uneven development in this area and pollution discharges, to which Qinghai province having the main contribution. Significant differences in the geographical distribution of pollution sources were illustrated in the QTP (Fig. 4b-d). Due to the implementation of an "ecological resettlement" project, pollution discharges dramatically decreased in the Sanjiangyuan area in the southern part of Qinghai Province, however, it dramatically increased in the northeastern area. Despite a slowdown in China's macroeconomic economy, Qaidam basin has maintained a rapid annual growth rate of +8.53% over the last ten years. In Tibet, total pollution discharge has decreased due to changed farming style by the reduced number of nomadic livestock, and development was limited in the eastern Lhasa Valley Plain and Nyingchi. Consistent trends of nutrient concentration and regional pollution discharge indicate that an intensification of anthropogenic activities and rapid socio and economic growth are dominant factors enhancing TN and TP content in the QTP lakes. Further investigations are required to propose alternative methods and to produce more conclusive results for determining the contribution to various factors influencing water quality in the QTP lakes.

4.3 Implications for the Qinghai-Tibetan lake region's protection in future

By reviewing the water environment in China in the last half-century, it is evident that management practices have not stepped off the well-trodden path of "pollution first, treatment afterward." Huge investment since 2000s, mainly focusing on the construction of point-source controls(Table S5), succeeded in immediately slowing the decline of water quality, but ecosystem restoration was not achieved. After ten years of treating Lake Taihu, costing 14.28 billion US$, water quality parameters have been improved. However, algae blooms have not been fully alleviated. In 2017, the maximum bloom area still occupied 2/3 of the lake surface area, and it was 66% larger than the bloom in 2007 (Qin et al., 2019). An unfortunate outcome of the nutrient reduction strategy suggests that the complexity and challenges associated with remediating lakes environment through intensive restoration activities, alone, is time-consuming and unpredictable due to the transition of ecological status (Folke et al., 2004; Scheffer et al., 2012).

In our study, the relationship between water quality decline and GDP growth rate in Lake Hurleg highlighted the intensified and imbalanced economic development in the QTP lake region could result in more rapid water quality degradation than other lake regions. Therefore, to protect the water quality and to undertake appropriate strategies and policy recommendations for governments relating to water quality protection in the QTP lake region, lessons learned and experience gained from the degradation of the east- and mid-China lakes must be incorporated. Thus, full protection should be prioritized in the QTP lake region, which is associated with the overall goal of the next stage of lake protection and management policy in China. In particular, concerning geographical characters and continued speeding up of economic growth, a transformation of development and protection strategies need to be accomplished, which is characterized by sustainable, low-emissions, high level of energy efficiency and environment-friendly, as well as highly relevant management. In particular, water-saving measurements must be adopted in the industry to ensure ecological water demand, land and resource utilization for agriculture and livestock farming must be limited to fall within the current environmental carrying capacity. At present, a series of protection measures have been adopted, such as establishing nature reserves, national Parks, and ecological restoration. Since 2014, 10.19 million US$ has been invested in supporting key lakes in this region, including Nam Co, Yamdrok Co, Lake Hurleg, and the Yellow River source lakes in terms of ecological restoration. In the future, appropriate environmental governance and ecological restoration, systematic monitoring of major lakes and further in-depth research in supporting water quality and water environment management need to be promoted

5. Conclusion

The results from our study identified a rising trend of nutrient concentration in the QTP lake region over the last 30 years and demonstrated the rapid deterioration of the water environment in Lake Hurleg due to extensive development. The dynamic response of water quality in Lake Hurleg to economic proxy indicated that current rapid and intensive development models could result in serious and irreversible impacts on QTP lakes.

As we showed, lakes are less resilient to internal and external driving variables in the QTP region, as well as the inconclusive restoration approaches used in China suggest that greater importance must be immediately attached to emerging trends of water pollution in the QTP lake region and stringent protection standards may be needed to ensure successful protection goals.

Conflict of interest

The authors declare that they have no conflict of interests.

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