

Coupling effects of hydrological characteristics and nutrient load in sediments on the trophic state of reservoirs

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Received: 21 March 2021 / Revised: 21 April 2021 / Accepted: 23 May 2021 / Published online: 2 June 2021
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Abstract Currently, lakes and artificial reservoirs are increasingly threatened by eutrophication, which is the result of the combined action of many natural and anthropogenic factors. In the past, the effect of nutrient load on the trophic state of water bodies has attracted much attention, while few studies have addressed the effect of hydrological characteristics. Therefore, to reveal the coupling effects of hydrological characteristics and nutrient load in sediments on the trophic state of water bodies, this study collected relevant data from 36 lakes and reservoirs across China. Pearson correlation analysis showed that

trophic level index was positively and significantly correlated with nutrient load in sediments and hydraulic retention time, while it was negatively correlated with mean depth and hydraulic load. The principal component analysis showed that the nutrient load was the first major component that influenced the trophic state of water bodies, followed by the mean depth and hydraulic retention time. Eutrophication was prone to occur in water bodies with mean depth less than 7 m and hydraulic retention time greater than 14 d, and the trophic level index regression equation with hydrological characteristics and nutrient load in sediments was derived by multiple regression analysis. This study revealed that the trophic state of water bodies influenced by both nutrient load and hydrological characteristics. It provides a new idea to reduce the occurrence of eutrophication in reservoirs by using the artificial hydrological regulation capacity of reservoirs.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11631-021-00478-y>.

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Keywords Artificial reservoirs · Hydrological characteristics · Nutrient load · Trophic state of water bodies

1 Introduction

Artificial reservoirs and lakes are closely related to human life and provide important needs for human society, such as freshwater, electricity, shipping, leisure, aquatic products, etc., and have great economic and social value (Beklioglu et al. 2010). The development of human society depends to a large extent on freshwater. At the same time, human activities have also greatly changed the water environment of lakes and reservoirs (Chuai et al. 2012). In recent decades, due to large-scale urbanization, industrialization, and agricultural production, large amounts of nitrogen,

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phosphorus, and other nutrients have been discharged into lakes, reservoirs, estuaries, and bays, thereby accelerating the eutrophication of water bodies (Morgane et al. 2019; Huang et al. 2017a, b; Qin et al. 2013). The rapid growth of algae and other planktonic organisms has resulted in the deterioration of water quality and the gradual loss of structure and function of aquatic ecosystems (Western 2001; Li et al. 2014). Currently, eutrophication has become one of the most common and serious environmental problems in the world (Jin et al. 2005; Yang et al. 2008).

Eutrophication is widely regarded as a response to increased nutrient load (Verspagen et al. 2006). Therefore, the relationship among factors such as point source pollution, nonpoint source pollution, land use patterns, and trophic state of water bodies has been extensively studied (Galbraith and Burns 2007; Fraterrigo and Downing 2008). To control the occurrence of eutrophication, many countries have formulated a series of policy objectives. For example, the Water Framework Directive (WFD) formulated by the European Union and the Water Pollution Prevention and Control Law of the People's Republic of China formulated by China in 2008. Eutrophication in water bodies can be mitigated by reducing the external nutrient load and controlling internal pollution. It has been alleviated to a certain extent, but the problem still exists (Jeppesen et al. 2007; Søndergaard et al. 2005; Parris 2011). For example, in the Taihu Lake (in China), after a series of rectification measures, the nutrient load in the sediment was relatively low, e.g., TP_{sediment} (total phosphorus in sediment) < 600 mg/kg, but the water body remained in a eutrophic state (Li et al. 2012; Yang et al. 2014). Moreover, deep lakes such as Fuxian Lake and Lugu Lake, which had a high nutrient load in sediments (e.g., $TP_{\text{sediment}} \geq 2000$ mg/kg), remained in a state of oligotrophy (Wang et al. 2010; Chen and Xu 2016). This observation indicates that hydrological characteristics such as water depth may play an important role in the trophic state of water bodies. However, the coupling effects of hydrological characteristics and nutrient load on the trophic state of water bodies are still not well understood. Therefore, understanding the effects of factors on the trophic state of water bodies is an important issue facing the current water environment.

With the development of the social economy, human society's demand for water energy and water resources is growing rapidly. This has greatly strengthened the development and utilization of rivers by human society. Dam interception can significantly alter the physical, chemical, and biological processes of rivers, the most obvious phenomenon being the reduction of suspended particulate matter concentration and turbidity (Xiao 2017; Gao et al. 2013). In addition, river impoundment can also lead to an increase in the HRT (hydraulic retention time) of

reservoirs, the development of seasonal thermal stratification in water bodies, *in-situ* increase in primary production, and a decrease in turbulence (Wang, 2020; Friedl and Wüest 2002). These changes have important impacts on the nutrient cycle of water bodies and even lead to the deterioration of water quality, such as eutrophication. Unlike natural lakes that are regulated by natural laws and do not have the capacity for artificial hydrological regulation, the hydrological regime of artificial reservoirs is characterized by artificial regulation, especially in terms of water level and HRT (Yang et al. 2020; Han et al. 2018). Thus, it is essential to understand the coupling relationship between the mean water depth (Z_{mean}), HRT, hydraulic load (H_L) (defined as the ratio of Z_{mean} to HRT), and trophic state parameters of water bodies, which can help to mitigate the eutrophication state of water bodies using the artificial hydrological regulation capacity of the reservoirs.

In this study, 36 lakes and reservoirs with different hydrological characteristics and nutrient load in sediments, as well as the trophic state of water bodies, were investigated. The objectives of this study were (1) to investigate the coupling effects of hydrological characteristics and nutrient load in sediments on the trophic state of lakes and reservoirs; (2) to reveal the reservoirs' capacity of artificial hydrological regulation on the trophic state of water bodies and to provide practical significance in water quality protection of the global environment.

2 Material and method

2.1 Data collection

In this study, data related to lakes and reservoirs were collected from published reports, with 13 sites belonging to natural lakes and 23 sites belonging to reservoirs, amounting to a total of 36 (Fig. 1). The data comprises three categories: trophic state parameters, nutrient load parameters, and hydrological characteristics parameters (Table S1). Trophic state parameters include comprehensive trophic level index (TLI), total nitrogen (TN_{water}), total phosphorus (TP_{water}), chlorophyll-a (Chl-a), chemical oxygen demand (COD_{Mn}), and Secchi depth (SD) (to distinguish sediment parameters from those in water bodies, the parameters in the sediment were added with the subscript "sediment", and in water bodies, they were added with the subscript "water", as shown in Table 1). Nutrient load parameters include total phosphorus contents in the sediment (TP_{sediment}) and phosphorus fluxes at the water–sediment interface (F). Since previous studies have shown that most freshwater lakes exhibit phosphorus limitation for primary production, phosphorus plays a dominant role in controlling the trophic state of water

Fig. 1 Locations of the 36 Chinese lakes and reservoirs were evaluated in this study. Each circle corresponds to one sampled site; The five-pointed star stands for Beijing

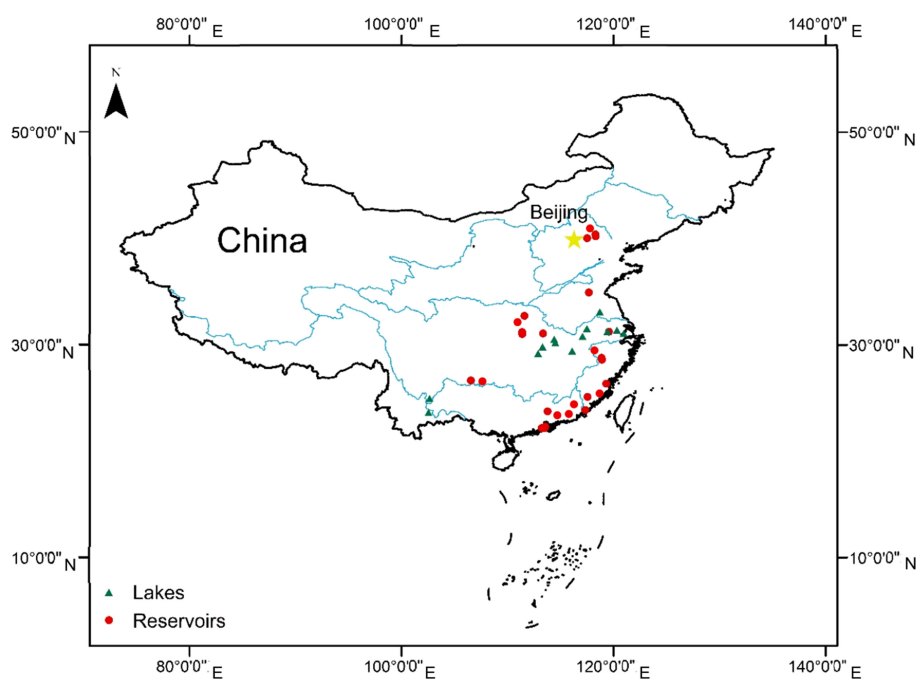


Table 1 Summary for statistics of hydrological characteristics, nutrient load and trophic state variables used in this study

Variable	Unit	Abbr	Minimum	Maximum	Mean	sd ^a
<i>Hydrological characteristics</i>						
Mean water depth	m	Z_{mean}	2.00	67.00	14.99	14.50
Hydraulic retention time	d	HRT	4.00	1 423.00	165.55	249.79
Hydraulic load	m/d	H_L	0.004	6.75	0.49	1.18
<i>Nutrient load</i>						
Total phosphorus in sediments	mg kg^{-1}	$\text{TP}_{\text{sediment}}$	205.00	2 838.00	969.62	673.17
Phosphorus flux at the water sediment interface	$\text{mg (m}^2 \text{ d)}^{-1}$	F	0.01	5.28	0.87	1.09
<i>Trophic state parameters</i>						
Total nitrogen	$\text{mg} \cdot \text{L}^{-1}$	TN_{water}	0.40	8.43	1.59	1.51
Total phosphorus	mg L^{-1}	TP_{water}	0.01	0.72	0.11	0.14
Chemical oxygen demand	mg L^{-1}	COD_{Mn}	1.00	12.29	3.85	2.55
Chlorophyll-a	mg m^{-3}	Chl-a	0.96	39.91	12.29	10.55
Secchi depth	m	SD^b	0.28	7.10	1.52	1.44
Comprehensive trophic level index		TLI	23.50	72.60	46.36	10.46

^a“sd^a”: standard deviation; ^b“SD^b”: Secchi depth

bodies (Qin et al. 2020). Hydrological characteristics parameters include the Z_{mean} , HRT, and H_L . H_L is calculated using the following formula (Wollheim et al. 2006):

$$H_L = \frac{Z_{\text{mean}}}{\text{HRT}} \quad (1)$$

where Z_{mean} (m) is the mean water depth of reservoirs and lakes, and HRT(d) is the hydraulic retention time of reservoirs and lakes.

To minimize the impact of climate due to the limitations of data collection, this study prioritized the recording of data for the same year and month.

2.1 Calculation

The comprehensive trophic level index was calculated using the following formula (Wang et al. 2002):

$$TLI(\sum) = \sum_{j=1}^m W_j \times TLI_j \quad (2)$$

where $TLI(\sum)$ is the comprehensive trophic level index, m is the number of evaluation parameters, W_j is the weight of the trophic status index of the j th parameter, TLI_j is the trophic status index of the j th parameter.

$$TLI(Chl - a) = 10 \times (2.5 + 1.086 \times \ln Chl - a) \quad (3)$$

$$TLI(TP_{water}) = 10 \times (9.436 + 1.624 \times \ln TP_{water}) \quad (4)$$

$$TLI(TN_{water}) = 10 \times (5.453 + 1.694 \times \ln TN_{water}) \quad (5)$$

$$TLI(SD) = 10 \times (5.118 - 1.94 \times \ln SD) \quad (6)$$

$$TLI(COD_{Mn}) = 10 \times (0.109 + 2.661 \times \ln COD_{Mn}) \quad (7)$$

where Chl-a and SD units are $\mu\text{g/L}$ and m , respectively, and other indicators are in mg/L .

2.2 Assessment standard

The result of TLI calculation is a value between 0 and 100, based on the following standards: oligotrophy ($TLI < 30$), mesotrophy ($30 \leq TLI \leq 50$), and eutrophication ($TLI > 50$), including mild eutrophication ($50 < TLI \leq 60$), moderate eutrophication ($60 < TLI \leq 70$), severe eutrophication ($TLI > 70$) (Wang et al. 2002).

Changes in TN/TP stoichiometry may indicate altered patterns of phytoplankton nutrient limitation. Based on thresholds derived from global patterns of phytoplankton stoichiometry, the potential N only limitation is indicated when $N/P < 9.0$, N + P co-limitation is indicated when $9 \leq N/P < 22.6$, and P only limitation is indicated when $N/P \geq 22.6$ (Guildford and Hecky 2000).

According to the “Environmental quality assessment standard for nutrients in sediments” issued by the Ontario Ministry of Environment and Energy in 1999, the assessment criteria are as follows: security level ($TP_{\text{sediment}} < 600 \text{ mg/kg}$), lowest level ($600 \text{ mg/kg} \leq TP_{\text{sediment}} < 2000 \text{ mg/kg}$), and severe level ($TP_{\text{sediment}} \geq 2000 \text{ mg/kg}$) (Leivuori and Niemisto 1995).

2.3 Statistical analysis

All parameters (except TLI) were Ln-transformed to satisfy the assumption of normality prior to subsequent analysis. This study used Pearson correlation analysis to analyze the relationship between trophic state parameters, nutrient load parameters, and hydrological characteristics parameters. Principal component analysis (PCA) was then used to select the main driving factors of TLI (to avoid collinearity, H_L was not analyzed in the principal component analysis). Finally, the relationship between TLI and the main driving factors was analyzed using multiple regression analysis.

Statistica 22.0 was used for all statistical analyses. Scatter plots and fitted curves were drawn using origin 2018.

3 Result

Based on the TN/TP ratios in this study, 91.43% of all lakes and reservoirs exhibited potential P limitation (P only and N + P co-limitation), suggesting that P limitation is a key factor in controlling the trophic state of water bodies (Table S2).

The six typical water quality indicators (TLI, TN_{water} , TP_{water} , COD_{Mn} , Chla, and SD) were chosen to evaluate the influences of hydrological characteristics and nutrient load on the trophic state of water bodies. Pearson correlation analysis showed that TP_{sediment} and F were positively and significantly correlated with TLI, TN_{water} , and TP_{water} (Table 2). This result is consistent with the general view that the eutrophication of water bodies is a response to excessive input of nutrient loads. Z_{mean} was significantly and negatively correlated with TLI, TP_{water} , TN_{water} , COD_{Mn} , and Chl-a, while it was positively correlated with SD. HRT was significantly and positively correlated with TLI and COD_{Mn} only. H_L was significantly and negatively correlated with TLI, TP_{water} , COD_{Mn} , and Chla, while it was positively correlated with SD. The above analyses indicate that the lakes with larger Z_{mean} , shorter HRT, and higher H_L have better water quality.

PCA was used to determine the major driving factors of TLI. The combined score of the first three principal components was greater than 1; therefore, only the first three components were further examined, and their cumulative variance contribution rate was 68.494% (Figs. 2 and 3). The variance contribution rate of the first principal components was 27.051%. TP_{sediment} , F, TN_{water} , and TP_{water} largely accounted for the first principal component, with characteristic vectors of 0.858, 0.741, 0.664, and 0.646, respectively. The variance contribution rate of the second principal component was 25.820%, of which SD and Z_{mean} accounted for the largest principal component, with characteristic vectors of -0.850 and -0.821, respectively. Finally, the variance contribution rate of the third principal component was 15.624%, of which HRT and COD_{Mn} accounted for the largest principal component, with characteristic vectors of 0.900 and 0.699, respectively.

To further study the coupling effects of hydrological characteristics and nutrient load on the trophic state of water bodies, scatter plots of the relationship between nutrient load (e.g., TP_{sediment} and F), hydrological characteristics (e.g., Z_{mean} , HRT, and H_L), and TLI were drawn, as shown in Figs. 4 and 5. TLI was linearly correlated with increases in $\text{Ln}TP_{\text{sediment}}$, $\text{Ln}F$, and LnHRT , and decreases in $\text{Ln}Z_{\text{mean}}$ and $\text{Ln}H_L$ (Fig. 4). Notably, eutrophication

Table 2 Pearson correlation coefficients of trophic state parameters with nutrient load, and hydrological characteristics variables

TLI	*	***	***	*	**	***	***	***	***	***
.380*	HRT		***					**		
-.630***	-0.124	Z _{mean}	***				*	**	**	**
-.648***	-.814***	.677**	H _L		*	*	*	***	*	**
.395*	0.06	-0.026	-0.054	TP _{sediment}	**	*	*			
.516**	0.26	-0.299	-.378*	.543**	F	*	**			*
.672***	0.247	-0.333	-.381*	.431*	.377*	TN _{water}	**		**	*
.693***	0.182	-.389*	-.366*	.394*	.460**	.461**	TP _{water}		*	
.654***	.477**	-.482**	-.642***	0.16	0.218	0.272	0.22	COD _{Mn}	*	**
.796***	0.181	-.455**	-.407*	0.311	0.327	.456**	.374*	.390*	Chl-a	***
-.726***	-0.143	.601***	.466**	-0.222	-.410*	-.345*	-0.232	-.444**	-.629***	SD

“*”: significant at the 0.05 level; “**”: significant at the 0.01 level; “***”: significant at the 0.001 level

does not always occur in water bodies with high nutrient load ($TP_{\text{sediment}} \geq 600$ mg/kg) (Fig. 5). It may also occur in water bodies with low nutrient load in sediments ($TP_{\text{sediment}} < 600$ mg/kg), which mostly in Z_{mean} less than 7 m and HRT greater than 14 d. The results indicate that both hydrological characteristics and nutrient load are important to the trophic status.

The results of multiple regression analysis showed that TP_{sediment} , Z_{mean} , and HRT were the main predictors of TLI. The regression equation is shown as follows:

$$TLI = 11.635 + 5.760 \ln TP_{\text{sediment}} + 2.193 \ln HRT - 5.978 \ln Z_{\text{mean}} (R^2 = 0.624, P < 0.001)$$

The regression equation shows that the three predictors explain 62.4% of the variability in TLI, but there are still some factors that have not been taken into account. The regression equation was taken as a simple prediction model and the corresponding influence parameters were incorporated into the regression equation for backstepping (Fig. 6). The modeled data from the regression equation were compared with the observed data. As shown in Fig. 6, the simulation effect of the multiple regression equation prediction models is good (e.g., $R^2 = 0.60$, $P < 0.001$).

4 Discussion

4.1 Effect of nutrient load in sediments on the trophic state of water bodies

Of the many nutrients required for phytoplankton growth, P is the most important nutrient that limits algal growth (Smith et al. 1999). This study demonstrated that 91.43% of all lakes and reservoirs exhibited potential P limitation (P only and N + P co-limitation). TP_{sediment} , F, and TP_{water} were positively and significantly correlated with TLI and largely accounted for the first principal component (Table 2 and Fig. 3). Therefore, they may be the first principal component, which possibly can be attributed to the effect of nutrient load on the trophic state of water bodies. This indicates that nutrient load is the primary factor affecting the trophic state of water bodies. In recent years, many countries have sought to reduce point and nonpoint-source pollution to protect the water environment (Wang et al. 2021; Le et al. 2010; Ayele and Atlabachew 2021; Zaragueta and Acebes 2017). However, the nutrient load in some watersheds cannot be reduced rapidly. This is because nutrient loads from industrial wastewater are reduced, but nutrient loads from agricultural dispersed

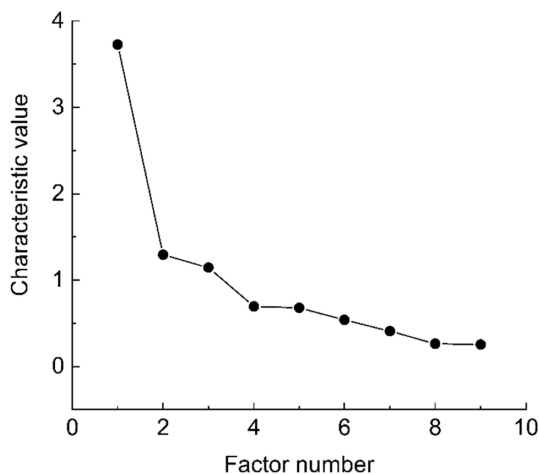


Fig. 2 Scree plot of PCA (principal component analysis)

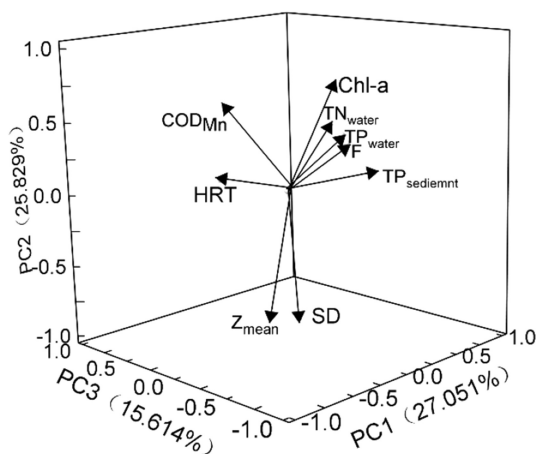


Fig. 3 Factor loading plots of PCA (principal component analysis)

sources remain high, especially in countries with intensive agriculture (Vander Molen and Portielje 1999; Le et al. 2010). Besides, the influence of internal nutrient load on the trophic state of water bodies has become more important than ever (Jeppesen et al. 2005). As a result, the frequent eutrophication in some water bodies is mitigated. However, the water quality of some shallow water reservoirs and lakes recovered slowly, and the trophic state of water bodies remained high for a long time (Jeppesen et al. 2007; Søndergaard et al. 2003). Therefore, a new approach is needed to mitigate the eutrophication of water bodies under the condition that both internal and external water sources cannot be rapidly reduced.

4.2 Effect of mean depth on the trophic state of water bodies

Z_{mean} is one of the most important parameters of lake morphology, which reflects the dilution and buffering

capacity of water bodies to nutrient loads, and has an important effect on the dynamic nutrient cycle of water bodies (Muller et al. 1998; Taranu and Irene 2008). In this study, Z_{mean} was negatively correlated with TLI, TP_{water} , COD_{Mn} , and Chl-a, while it was positively correlated with SD, constituting to a large extent the second principal component and a major predictive factor of TLI (Table 2 and Fig. 3). This reflects the controlling effect of Z_{mean} on the trophic state of the water body and indicates that deep lakes and reservoirs are less eutrophic than shallow ones.

For shallow lakes and reservoirs, they will be susceptible to wind and wave disturbances that cause sediment resuspension and promote the transformation and release of nutrients from the sediment (Cai et al. 2007; Liu et al. 2010). For example, several studies have found that sediments in Taihu Lake ($Z_{\text{mean}} = 2$ m) produce peaks in nutrient release during the period of wind and wave disturbance. As a result, TN_{water} and TP_{water} increased by 0.12 mg/L and 0.005 mg/L, respectively (Qin et al. 2004). Similarly, under the turbulence of wind and waves, in Dianshan Lake ($Z_{\text{mean}} = 2$ m), the dynamic flux of soluble reactive phosphate (SRP) was 20.22 mg/(m²d), 2.2 times higher than the static flux (Sun et al. 2016). The nutrient load buried in sediments is much heavier than in water. As such, a small amount of sediment release alone will greatly increase the nutrient content of the water. Therefore, when Z_{mean} was less than 7 m, the trophic state of some water bodies also reached eutrophication standards despite their low sediment nutrient load ($\text{TP}_{\text{sediment}} < 600$ mg/kg) (Fig. 5).

For deep lakes and reservoirs, they are prone to the development of thermal stratification in the water body (Liu et al. 2019). It can hinder material transfer and energy exchange between the upper and lower layers of the water body, which leads to the nutrients being hindered in vertical circulation and inhibits nutrient demand for phytoplankton production (Jones and Poplawski 1998). In Fig. 5, when Z_{mean} was greater than 7 m, the nutrient load of sediments in some water bodies was very high ($\text{TP}_{\text{sediment}} \geq 2000$ mg/kg) and the water bodies remained in a state of oligotrophy or mesotrophy. Therefore, despite the great efforts made worldwide to control eutrophication in different lakes, almost all successful cases come from deep lakes (Havens et al. 2007). The mitigation of eutrophication in shallow lakes is usually much more difficult compared to deep lakes (Qin et al. 2006, 2020; Nöges et al. 2007).

4.3 Effect of hydraulic retention time on the trophic state of water bodies

Generally, HRT represents the stability of hydrodynamic conditions and the washing rate of the water body. When

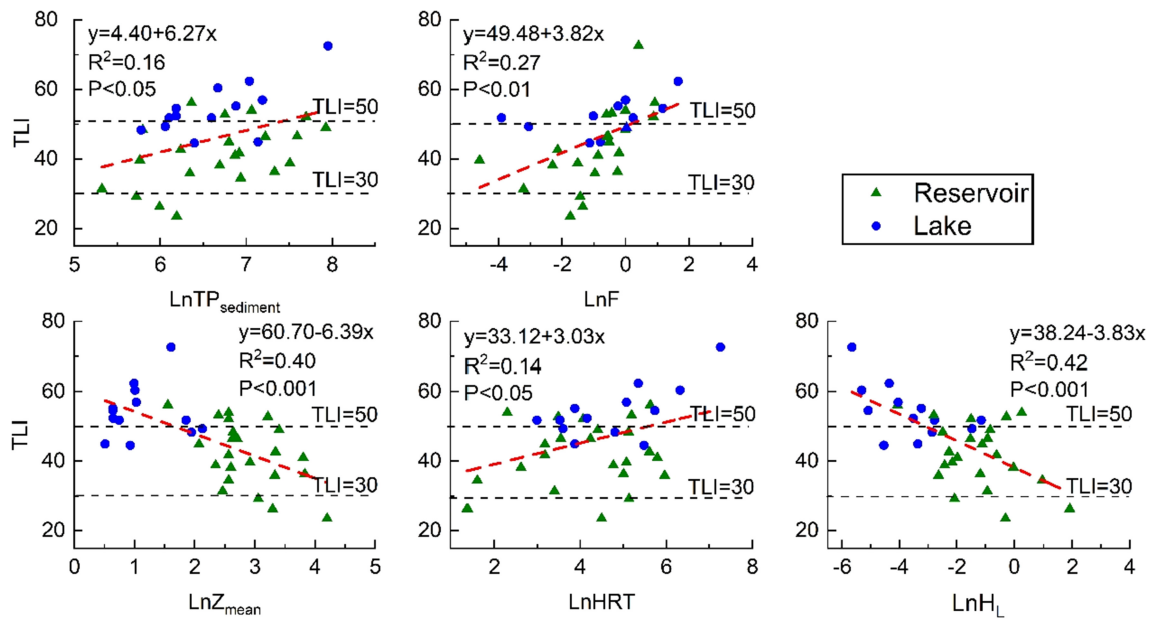
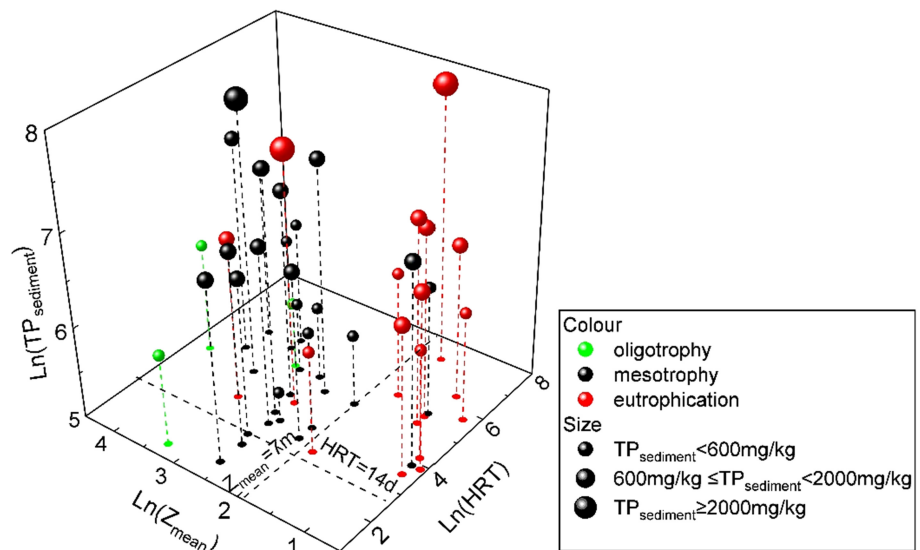


Fig. 4 The influence of hydrological characteristics and nutrient load in sediments on TLII. **a** The linear relationship between TLII and $\ln TP_{\text{sediment}}$; **b** The linear relationship between TLII and $\ln(F)$; **c** The linear relationship between TLII and $\ln(Z_{\text{mean}})$; **d** The linear relationship between TLII and $\ln(HRT)$; **e** The linear relationship between TLII and $\ln(H_L)$

Fig. 5 The scatter plot of 36 lakes and reservoirs



the HRT is short, the shear force generated by higher flow rates does not create a good growth environment for phytoplankton and inhibits phytoplankton growth. It usually takes at least 2 weeks for full phytoplankton growth (Wu and Li 2010; Beklioglu et al. 2010; Jones and Elliott 2007; Ferris and Lehman 2007). Moreover, the shorter the HRT, the faster the removal of nutrients, and the fewer nutrients are available to the phytoplankton, the lower the primary productivity; conversely, the longer the HRT, the greater the primary productivity of the promoted phytoplankton (Vollenweider 1975; Brett and Benjamin 2008). This study revealed a significant positive correlation between HRT

and trophic state parameters. HRT was the third principal component and main predictive factor of TLII. Besides, it is worth noting that due to the influence of HRT on the trophic state of water bodies, in Fig. 5, when the HRT is less than 14 d, there is no eutrophication; when it is greater than 14 d, eutrophication starts to occur in some water bodies. Among them, the nutrient load in the sediment of some water bodies was very low ($TP_{\text{sediment}} < 600 \text{ mg/kg}$) and the water bodies were still in a state of eutrophication. These prove that HRT plays an important role in controlling the trophic state of water bodies. It is consistent with

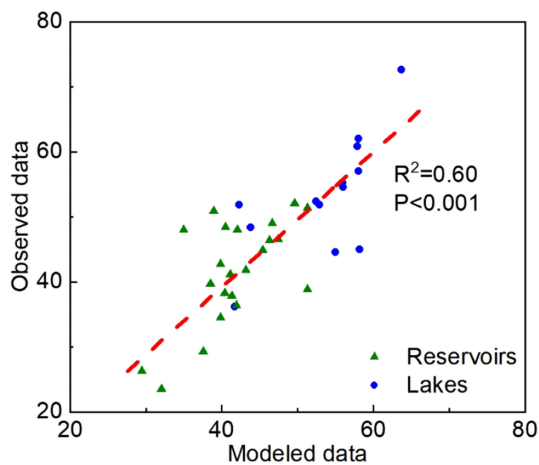


Fig. 6 Regression analysis between the modeled and observed data of TLI

the results of previous studies that water bodies with longer HRT are more prone to eutrophication (Lin et al. 2010).

The measures of changing HRT to mitigate eutrophication have already been applied in practice. For example, the “water diversion project from the Yangtze River to Taihu Lake” was launched in 2002, which diverted the Yangtze River water from the Wangyu River to Taihu Lake and finally flowed out from the Taipu River (Pan et al. 2015; Ma et al. 2014). The HRT of Taihu Lake was shortened from 300 days to about 250 days (Xu et al. 2020). In this way, the water circulation in Taihu Lake was accelerated and the water quality was improved (Gao et al. 2006). Within 10 years, the COD_{Mn} of Taihu Lake reached the level of class II, $\text{NH}_4^+\text{-N}$ reached the level of class I, and TN increased from inferior class V to class V (indicators refer to the “Environmental quality standard for surface water” (GB 3838–2002), and water quality standards are classified from high to low into class I to V) (Zhou et al. 2015; Huang et al. 2017a, b).

4.4 Effect of hydraulic load on the trophic state of water bodies

H_L is a comprehensive hydrological characteristic parameter combined with Z_{mean} and HRT, representing the water column height of one square meter of water surface flowing through the lake and reservoir system per unit time, and controlling the retention rate of nutrients in the water. Under the same nutrient load, the higher the H_L value, the lower the retention rate of N and P nutrients (Kelly et al. 1987; Behrendt and Opitz 1999). Therefore, a high value of H_L will inhibit the growth of algae, weaken the primary productivity of water bodies, and alleviate the trophic state of water bodies. In this study, H_L was negatively correlated with Chl-a and TLI, indicating that H_L has an important

controlling effect on the trophic state of water bodies (Table 2).

It is worth noting that, although hydrological characteristics have an important impact on the trophic state of water bodies, the nutrient load is still the primary factor affecting the trophic state. For lakes, the hydrological characteristics are also effective in controlling the trophic state. However, lakes are regulated by nature without the artificial regulation capacity. Therefore, more effort should be put to reduce the nutrient load for shallow lakes with long HRT. And for reservoirs, artificial regulation capacity can be used to manage the trophic state of water bodies by changing the water level, hydraulic retention time, and hydraulic load.

5 Conclusion

Based on the analysis of 36 lakes and reservoirs, this study found that both the hydrological characteristics and nutrient load played an important role in controlling the trophic state of water bodies. Nutrient load is the main factor affecting the nutrient state, followed by hydrological characteristics. More than 90 percent of the studied lakes and reservoirs showed potential phosphorus limitation characteristics, suggesting that phosphorus control is critical to mitigating eutrophication. In terms of hydrological characteristics, shallow reservoirs and lakes are more prone to eutrophication than deep ones. In addition, eutrophication is also prone to occur in reservoirs and lakes with longer hydraulic retention times. This study showed that, due to the coupling effects of hydrological characteristics and nutrient load on the trophic state of water bodies, eutrophication tends to occur in reservoirs and lakes with Z_{mean} less than 7 m and HRT greater than 14 days. This study illustrates that the artificial hydrological regulation ability can be used as an effective tool to guide the water environment management of reservoirs.

Acknowledgements This study was funded by the Shanghai Science and Technology Development Foundation (19010500100) and the National Key Research and Development Program of China (No. 2016YFA0601003).

Data availability All data generated and analyzed during this study are included in this published article and its supplementary information files.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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