Effects of extreme water levels on water quality in a large shallow eutrophic lake (Changhu Lake, China)

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Abstract

Changhu Lake, a large shallow eutrophic lake in central China, experienced an extreme low water level event from November 2015 to January 2016 followed by an extreme high water level event in July 2016. In this study, we examined the effects of two extreme water levels on the nutrient status of Changhu Lake over five years. The nutrient concentrations in Changhu Lake showed significant interannual variations and the water quality of sites in the western part of Changhu Lake was better compared to sites at the outlet of the lake. In late 2015, the effect of low water levels led to a significant increase in nutrient concentrations. After July 2016, however, the high water level occurred leading to a marked decrease in nutrient concentrations. These changes in nutrient parameters were strongly related to the water level fluctuations. The dilution effect was the key process that determined the variations of nutrient parameters in Changhu Lake. As extreme water levels are likely to become more frequent during the twenty-first century, this work may provide some insights into the conservation and management of lake ecosystems in the face of climate change and human activity.

Introduction

Natural lakes play an important role to preserve the economic and social sustainable development by providing food, transportation, recreation, and drinking water¹. China has a large number of lakes and more than 2690 natural lakes with an area of over 1 km²². Currently, with the rapid urbanization, population growth, and economic development, eutrophication has become the main driving force of water quality issues (i.e. an excessive increase in algae productivity) for many lakes due to the substantially increased amount of nutrients like nitrogen and phosphorus from the external environment^{3–5}. Specially, some lakes tend to be highly resistant to recovery^{6,7}. Therefore, maintaining the health of lake water has become an increasingly important objective of local government or decision makers.

Hydro-morphological stress is becoming one of the key ecological processes that influence the ecological integrity of global aquatic ecosystems^{8–10}. Hydrological regimes can affect aquatic communities, nutrient dynamics, seston composition, and other attributes of aquatic ecosystems in direct and indirect ways^{11,12}. For example, water level fluctuations (WLFs) can indirectly affect the seasonal variation of bacterial communities by controlling the optimum levels of nutrient availability in lake ecosystems¹³. As a significant element of hydrological regimes and a natural phenomenon that emerges in most aquatic ecosystems, WLFs have caused a wide range of attention, yet the influence of WLFs is still not fully understood^{10,14,15}.

Most lake ecosystems are subject to natural changes in water level on shorter to longer time-scales¹⁶. Natural variations in water level are essential for the survival of some aquatic communities and can generate more diverse and productive habitats^{14,17,18}. However, humans have altered the natural patterns of WLFs through the construction of dams, the abstraction of water, and climate change¹⁹. Extreme water

levels could potentially affect the limnological characteristics of the whole lake system, such as nutrient dynamics^{20,21}, community structure and interactions^{8,14}, and water residence times²². WLFs can influence internal nutrient mixing and convert monomictic lakes to polymictic ones⁹. At lower water levels, an increase in nutrient availability has been observed by some previous studies^{17,20,21,23}. Thus, water level management can be considered as a potential tool for freshwater ecosystems to improve water quality^{17,21}. Previous studies have shown that shallow lakes are especially sensitive to WLFs and relatively minor changes in water level can be translated to large variations in lake surface area and water volume^{13,24}. Further, shallow lake ecosystems may be dramatically impacted when water level changes between 1m and 2 m²⁰.

Given the changes in water level is predicted to be of more frequent occurrence in lake ecosystems worldwide, in this work, we aimed to: (1) investigate the spatial and temporal variations of nutrient parameters related to the extreme water levels; (2) examine the relationships between lake nutrients and water levels. Based on our results, we sought to predict the impacts of extreme water regimes on the water quality of the lake and provide a potential tool for future lake management.

Results

Spatial and temporal variations in nutrient concentrations

The spatial patterns of the nutrient parameters varied across the sampling sites (Figs. 1 and 2). The concentrations of TN, NH₄-N, and TP were significantly different ($P < 0.001$) between the different sampling sites. In S4, TN, NH₄-N, and TP concentrations were significantly lower than in other sampling sites, with mean values of 2.02 ± 0.51 , 0.61 ± 0.19 , and 0.11 ± 0.04 mg/L, respectively. COD_{Mn} concentration in Changhu Lake varied between 1.77 and 6.87 mg/L throughout the sampling period, with a mean value of 4.16 ± 0.90 mg/L. No significant differences in COD_{Mn} concentrations were found between the four different sampling sites.

The nutrient parameters of Changhu Lake showed significant interannual variations ($P < 0.05$, Fig. 1). The highest TN (3.11 ± 0.59 mg/L) and NH₄-N (0.94 ± 0.29 mg/L), and the lowest COD_{Mn} (3.62 ± 0.82 mg/L) concentrations were recorded in 2016, while the highest TP (0.19 ± 0.06 mg/L) and COD_{Mn} (4.85 ± 0.53 mg/L) concentrations were observed in 2014. TN (2.12 ± 0.50 mg/L), NH₄-N (0.71 ± 0.20 mg/L), and TP (0.15 ± 0.04 mg/L) concentrations were significantly lower ($P < 0.05$) in 2017. COD_{Mn} concentration did not vary significantly between 2016 and 2017 (3.72 ± 0.58 mg/L). Thus, the water quality in 2017 may be the best throughout the whole study period concerning TN, NH₄-N, TP, and COD_{Mn}.

Seasonal variations in nutrient concentrations showed the opposite trend to sites (Fig. 2). TN, NH₄-N, and TP had a similar seasonal variation. The minimum and maximum concentrations of TN (2.30 ± 0.66 and 2.66 ± 0.82 mg/L), NH₄-N (0.73 ± 0.23 and 0.87 ± 0.29 mg/L), and TP (0.15 ± 0.05 and 0.17 ± 0.06 mg/L) occurred in March and November, respectively. No significant differences in the concentrations of TN,

NH₄-N, and TP were found between the different seasons. COD_{Mn} concentration was significantly different ($P < 0.05$) between the different seasons. The highest COD_{Mn} concentration was detected in January (4.55 ± 0.65 mg/L) and the lowest COD_{Mn} was measured in September (3.61 ± 0.96 mg/L).

Overall, the nutrient status in Changhu Lake showed a distinct pattern of variation over the study period (Fig. 3). The non-metric multidimensional scaling (MDS) had stress values lower than 0.15, indicating the ordination patterns of nutrient parameters in Changhu Lake were acceptable. The results of ANOSIM revealed that the distribution of nutrient parameters was significantly different among years (Global $R = 0.206$, $P = 0.001$), sampling sites (Global $R = 0.116$, $P = 0.001$), and phases (Global $R = 0.191$, $P = 0.001$) related to the extreme water levels (Fig. 3a,c,d). Seasons (Global $R = 0.006$, $P = 0.327$) presented R -value close to 0, indicating a high degree of seasonal similarity (Fig. 3b).

Relationships between nutrient concentrations and water levels

The relationships between water levels and nutrient concentrations were complex. Linear regression revealed that TN and NH₄-N concentrations were significantly ($P < 0.01$) and positively correlated with water levels (Fig. 4a,b), while TP and COD_{Mn} concentrations did not have a significant ($P > 0.05$) relationship with water levels (Fig. 4c,d). Despite this, TP concentration showed a positive correlation with water levels, COD_{Mn} concentration, in contrast, was negatively correlated with water levels.

The extreme water levels had different impacts on nutrient concentrations in Changhu Lake (Fig. 5). A significant increase in nutrient concentrations was observed during the LWL event. In contrast, nutrient concentrations exhibited an abrupt and significant decline following the HWL event. Total nitrogen (TN) was significantly different ($P < 0.001$) between the three phases related to the extreme water levels (Fig. 6a; Table 1). The highest TN was recorded after the LWL event from November 2015 to January 2016 (After), with a mean value of 3.29 ± 0.55 mg/L. During the pre-LWL period (Before) and the end of the time slices (Present), TN was significantly lower than during the after LWL period, with mean values of 2.62 ± 0.48 and 2.28 ± 0.52 mg/L, respectively. Variability of ammonia nitrogen (NH₄-N) exhibited a similar trend with TN (Fig. 6b; Table 1). NH₄-N in the After phase (1.06 ± 0.24 mg/L) was significantly ($P < 0.001$) higher than in the Before (0.79 ± 0.20 mg/L) and Present (0.74 ± 0.21 mg/L) phases. No significant differences in NH₄-N were found between the Before and Present phases. Total phosphorus (TP) in the Present (0.15 ± 0.05 mg/L) phase was significantly ($P < 0.001$) lower than in the Before (0.18 ± 0.05 mg/L) and After (0.19 ± 0.06 mg/L) phases (Fig. 6c; Table 1). TP did not vary significantly between the different phases related to the LWL event. Chemical oxygen demand (COD_{Mn}) showed the same pattern as TP with the lowest value in the Present (3.85 ± 0.80 mg/L) phase (Fig. 6d; Table 1). Despite this, COD_{Mn} in the After phase (4.31 ± 1.10 mg/L) was significantly ($P < 0.05$) lower than before the LWL event (4.62 ± 0.69 mg/L).

Table 1
Minimum, maximum, median, mean, standard deviation (SD), and number of values (*n*) for several nutrient parameters during the three periods related to the extreme water levels in Changhu Lake from 2014 to 2018.

Parameters		Min	Max	Median	Mean	SD	<i>n</i>
TN (mg/L)	Before	1.62	3.47	2.51	2.62	0.48	41
	After	2.02	4.25	3.28	3.29	0.55	15
	Present	1.13	3.29	2.17	2.28	0.52	54
NH ₄ -N (mg/L)	Before	0.42	1.21	0.81	0.79	0.20	41
	After	0.69	1.54	1.06	1.06	0.24	15
	Present	0.35	1.24	0.72	0.75	0.21	54
TP (mg/L)	Before	0.06	0.26	0.19	0.18	0.05	41
	After	0.09	0.29	0.17	0.19	0.06	18
	Present	0.03	0.25	0.14	0.15	0.05	54
COD (mg/L)	Before	3.19	6.70	4.59	4.62	0.69	41
	After	3.21	6.87	3.88	4.31	1.10	19
	Present	1.77	5.60	3.83	3.85	0.80	55

Our correlation-based principal component analysis (PCA) clearly showed the loading of nutrient parameters before and in the aftermath of the extreme water levels (Fig. 7). The first component (PC1) was strongly and negatively correlated with TN, NH₄-N, and TP, suggesting a high nutrient load in the Before and After phases. The second component (PC2) was largely contributed by COD_{Mn} and represented a decline in organic matter after the HWL event (Present).

Discussion

The fluctuations of water level have been described as one of the main disturbances of aquatic ecosystems due to the combined effects of climate change and human activity^{8,14,25}. In fact, WLFs can affect nutrient dynamics by altering the water residence times²², vertical mixing regimes²⁶, and water-sediment interface²⁷. Here, we examined the impacts of extreme water levels on nutrient parameters in Changhu Lake in central China. Nutrient concentrations increased and decreased following a marked decline and rise of water levels, respectively. This result is consistent with a previous study in Poyang Lake²⁸, suggesting that water level was an important driver for nutrient variations. This is important because WLFs are likely to be more frequent occurrence under future predicted conditions of global warming and freshwater demands^{11,14,29}.

The concentration of nutrients in Changhu Lake has dramatically increased over the past few years because of considerable anthropogenic inputs from industrial, agricultural, and domestic wastewater³⁰. The nutrient parameters considered in this study show significant interannual variations. The lake had high nutrient concentrations during 2014–2016 and low during 2017–2018. Lake restoration projects, such as the removal of enclosure culture areas, artificial breeding and releasing of fish and benthos, cultivation of aquatic macrophytes, and ecological revetment for lake banks, may result in a decrease in nutrient concentrations and improve the lake water quality³¹. Meanwhile, an extreme high water level event was identified during the second half of 2016 and followed by an abrupt decline in nutrient concentrations due to strong dilution effects (Fig. 5). This feature suggests that the interannual variations of nutrient concentrations can be affected by both restoration efforts and hydrological changes.

Changhu Lake also shows seasonal variations in its nutrient concentrations during the study period, with the highest nutrient concentrations were observed in January and lowest in September. The present work demonstrated that the seasonal changes in nutrient concentrations varied with water level fluctuations. The concentrations of TN and NH₄-N increased with the rising water level, while TP and COD_{Mn} concentrations were not significantly correlated with water level fluctuations. This finding which is in accordance with previous results from both China's Poyang Lake²¹ and some stratified freshwater lakes⁹, indicates that water level fluctuations can regulate the internal nutrient concentrations of the lake.

The nutrient concentrations in Changhu Lake show significant spatial variations. Spatially, the nutrient concentrations at the outlet of the lake are different from that in those sites located in the western part of the lake. The field survey reveals that S1, S2, and S3 have higher concentrations of TN, NH₄-N, and TP due to receiving a large amount of pollutants from the Longhuiqiao, Taihugang, and Shiqiao rivers, which accounts for approximately 85% of the nutrient loads in Changhu Lake³². Consistent with the previous observations, site 4 has the lowest nutrient concentrations with relatively high COD_{Mn}. Such difference between the two parts of the lake may be attributed to the growth of aquatic plants, which would significantly decrease the concentration of nutrients and suspended particles³¹.

Our study revealed how the nutrient status of Changhu Lake varied depending on the fluctuations in water level. Similar results have been obtained in other works where water levels also have a significant effect on nutrient status^{11,33}. For example, Yang et al.¹¹ demonstrated that WLFs can influence cyanobacteria dynamics and cause an apparent switch between a turbid state and a clear state by modifying the nutrient loads and other limnological parameters in subtropical reservoirs. Wang et al.³³ found that water levels can significantly affect the nutrient status, phytoplankton growth, and gross primary productivity by indirectly influencing the fluctuations of water flow velocity and hydrological connectivity in Lake Poyang.

The nutrient status in Changhu Lake varied significantly throughout the study period related to the extreme water levels. The lake had the highest increase of all the nutrient parameters during and/or

following the extreme low water level (LWL) event. This increase may be associated with the combination of high precipitation (by a greater nutrient input) and artificial water transfer, which boosted the dominance of cyanobacteria³⁴. During the After period, the nutrient concentrations kept at high levels due to the stability of WLFs. TN, NH₄-N, and TP exhibited significant positive correlations with water levels. This was counter to Wang et al.³³, who found an inverse relationship between water levels and the concentrations of NH₄-N and dissolved TN. However, TP was significantly positively correlated to water levels, which was consistent with our results. During the Present period, water levels showed a negative correlation with COD_{Mn} and a declining trend in nutrient concentrations was observed following the extreme high water level (HWL) event. This result agrees with Yang et al.¹¹ who reported that due to the dilution effect, the positive WLFs can significantly reduce the nutrient concentrations. These findings provide support for other observational studies in rivers^{35,36}, lakes^{9,28,37,38}, and reservoirs^{11,39} that also found the variations of nutrient concentrations may be highly associated with WLFs.

Conclusion

This study highlights the impacts of extreme water levels on nutrient status in a large shallow eutrophic lake in central China. The nutrient parameters in Changhu Lake showed significant temporal variations over the study period, especially interannual ones. However, no significant spatial variations were found among these parameters, except for the samples that were collected at the outlet of the lake, which showed a relatively low nutrient status. The nutrient parameters significantly changed between the different phases related to the extreme water levels, with an increase during the After period and a decrease during the Present period. Dilution effect was identified as the key process that determines the variability of nutrient status in Changhu Lake. Given that the extreme water levels are likely to be of more frequent occurrence under future climate change and human activities, our research may be helpful for the conservation and management of Changhu Lake.

Materials And Methods

Study area

Changhu Lake is the third largest freshwater lake in Hubei Province, central China, located in Jiangnan Plain of the middle region of the Yangtze River basin (30°22'-30°31' N, 112°12'-112°30' E, Fig. 8). The surface area is approximately 140 km² and about 18 km wide at its widest zone, with a mean depth of 2.1 m and a normal water level of 30 m to 31 m. It receives inflows from the Longhuiqiao, Xiajiachong, Taihugang, Shiqiao, and Guangpinggang rivers, and connects to the Yangtze River through the Sihui Main Channel. The area is subject to a typical subtropical monsoon climate, with a mean annual temperature of 15.9–16.6°C and a mean annual total precipitation of 1100–1300 mm which is largely concentrated in the mid-spring to mid-autumn.

Changhu Lake plays an important role in controlling floods, supplying freshwater, fishery and aquaculture, and protecting biodiversity in the area. The lake is home to about 95 species of macrophytes, 77 species of fish, 29 species of birds (mostly migratory), 15 species of invertebrates, 12 species of reptiles, and 6 species of amphibians (Changhu Ecological Management Bureau, Jingzhou, China). However, Changhu Lake was classified as middle eutrophic ($60 \leq \text{TSI} \leq 70$) due to human activities (i.e. over-exploitation, pollution, and habitat destruction) and climate change⁴⁰, which causes strong degradation of biodiversity^{41,42}.

Sampling and sample analysis

Sampling campaigns were implemented at bimonthly intervals from 2014 to 2018 at four sites (Fig. 8). Site 1 (S1) was located in the western Changhu Lake, which is adjacent to the outlet of Longhuiqiao River. Site 2 (S2) and site 3 (S3) were located at the outlet of Taihugang River and Shiqiao River, respectively. Site 4 (S4) was situated at the outlet of Changhu Lake, of which the downstream is the Siyu Main Canal. Two liters of integrated surface water samples were collected at each site with pre-cleaned 5 L plastic buckets and preserved in a portable refrigerator before they were sent to the laboratory for further analysis. A total of 240 (4 sites $\times$ 6 months $\times$ 5 years) water samples were collected. The nutrient parameters, including total nitrogen (TN), ammonia nitrogen ($\text{NH}_4\text{-N}$), total phosphorus (TP), and chemical oxygen demand (COD_{Mn}), were measured following standard methods described by Greenberg et al.⁴³. Data on daily water levels were taken from the Water Resources Bureau of Hubei Province.

Statistical analysis

Extreme water levels are defined as the monthly water level anomalies above + 2 m/month or below - 2 m/month in relation to the mean of historical data²⁵. Across the whole 5-year time series, we identified one extreme low water level (LWL, November 2015 to January 2016) event and one extreme high water level (HWL, July 2016) event in Changhu Lake (Fig. 9). With this approach, the collected data were aggregated into three different phases: Before (samples from January 2014 to September 2015), After (samples from November 2015 to July 2016), and Present (samples from September 2016 to November 2018).

A multivariate technique, ANOSIM, was applied to examine the significant differences among individual years, seasons, sites, and different phases related to the extreme water levels for nutrient parameters (TN, $\text{NH}_4\text{-N}$, TP, and COD_{Mn}). Euclidean distance was calculated after the similarity matrix of the data set was $\log(x + 1)$ transformed. Non-metric multidimensional scaling (MDS) plots were built to explore the patterns of variations in nutrient parameters. Differences in nutrient parameters between different water level phases were tested using a one-way analysis of variance (ANOVA) for normally distributed data. Data normality was assessed using a Kolmogorov-Smirnov test. Principal component analysis (PCA) was performed to identify the overall trends in nutrient dynamics under different water level phases. All the statistical analyses were performed using the software packages PRIMER 7.0⁴⁴, SPSS 19.0 (SPSS Inc., Chicago, IL, USA), Statistica 10.0 (Statsoft Inc., Tulsa, OK, USA), and CANOCO for Windows 4.5⁴⁵.

Declarations

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Author Contributions

H.W. and J.R.Y. wrote the main manuscript text. J.R.Y. conceptualized the project. H.W., T.L., J.Z. and Z.L. conducted and interpreted the statistical analysis. All authors reviewed the manuscript prior to submission.

Competing interests

The authors declare no competing interests.

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Figures

Figure 1

Spatial and annual variations of (a) total nitrogen (TN), (b) ammonia nitrogen (NH₄-N), (c) total phosphorus (TP), and (d) chemical oxygen demand (CODMn) in Changhu Lake.

Figure 2

Spatial and seasonal variations of (a) total nitrogen (TN), (b) ammonia nitrogen ($\text{NH}_4\text{-N}$), (c) total phosphorus (TP), and (d) chemical oxygen demand (COD_{Mn}) in Changhu Lake.

Figure 3

Non-metric multidimensional scaling (MDS) plots of nutrient parameters in Changhu Lake for (a) different years, (b) different seasons, (c) different sampling sites, and (d) different phases related to the extreme water levels. Before, samples from January 2014 to September 2015; After, samples from November 2015 to July 2016; After, samples from September 2016 to November 2018.

Figure 4

Relationships between water level fluctuations (WLF) and seasonal changes in (a) total nitrogen (TN), (b) ammonia nitrogen ($\text{NH}_4\text{-N}$), (c) total phosphorus (TP), and (d) chemical oxygen demand (COD_{Mn}) in Changhu Lake. Solid lines indicate significant ($P < 0.05$) relationships.

Figure 5

Time series of (a) total nitrogen (TN), (b) ammonia nitrogen (NH₄-N), (c) total phosphorus (TP), and (d) chemical oxygen demand (COD_{Mn}) in Changhu Lake. LWL, low water level; HWL, high water level.

Figure 6

(a) total nitrogen (TN), (b) ammonia nitrogen ($\text{NH}_4\text{-N}$), (c) total phosphorus (TP), and (d) chemical oxygen demand (COD_{Mn}) in Changhu Lake during different phases related to the extreme water levels. Before, samples from January 2014 to September 2015; After, samples from November 2015 to July 2016; After, samples from September 2016 to November 2018.

Figure 7

Principal component analysis of nutrient parameters (solid lines with arrowhead) in Changhu Lake. The samples from January 2014 to September 2015 are shown as black (Before), the samples from November 2015 to July 2016 as red (After), and the samples from September 2016 to November 2018 as green (Present). TN, total nitrogen; $\text{NH}_4\text{-N}$, ammonia nitrogen; TP, total phosphorus; COD_{Mn} , chemical oxygen demand.

Figure 8

Location of Changhu Lake and four sampling sites in Hubei province, central China.

Figure 9

Extreme water level events recorded in over the full time series in Changhu Lake. LWL, low water level; HWL, high water level.