Effects of extreme water levels on nutrient dynamics 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 extremely low water level event from November 2015 to January 2016 followed by an extremely high water level event in July 2016. In this study, we examined the effects of two extreme water levels on the nutrient dynamics of Changhu Lake over five years. The nutrient parameters in Changhu Lake showed significant interannual variations, and the nutrient concentrations at the sites in the western part of Changhu Lake were 2–41% higher than those at the outlet of the lake. In late 2015, the effects of low water levels led to a 17–74% increase in nutrient concentrations. After July 2016, however, a high water level event occurred, leading to a 34–48% decrease in nutrient concentrations. These changes in nutrient parameters were strongly related to water level fluctuations ($p < 0.05$). 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
Hydro-morphological stress is becoming one of the key ecological processes influencing the ecological integrity of global aquatic ecosystems (Wantzen et al. 2008; Zohary and Ostrovsky 2011; Evtimova and Donohue 2016). Hydrological regimes can affect aquatic communities, nutrient dynamics, seston composition, and other attributes of aquatic ecosystems in direct and indirect ways (Yang et al. 2016; Liu et al. 2018a; Kenney and Waters 2019). For example, water level fluctuations (WLFs) can indirectly affect seasonal variation in bacterial communities by controlling optimum levels of nutrient availability in lake ecosystems (Ren et al. 2019). As significant elements of hydrological regimes and natural phenomena that emerge in most aquatic ecosystems, WLFs have attracted much attention, yet their influence is still not fully understood (Evtimova and Donohue 2016; Gownaris et al. 2018; Liu et al. 2020).
Most lake ecosystems are subject to natural changes in water level at short and long time scales (García-Molinos and Donohue 2014). Natural variations in water level are essential for the survival of some aquatic communities and can generate more diverse and productive habitats (Coops and Hosper 2002; Leira and Cantonati 2008; Gownarlis et al. 2018). However, humans have altered the natural patterns of WLFs through dam construction, water abstraction, and climate change (Haddeland et al. 2014). Extreme water levels could potentially affect the limnological characteristics of the entire lake system, such as nutrient dynamics (James and Havens 2005; Li et al. 2016), community structure and interactions (Wantzen et al. 2008; Gownarlis et al. 2018), and water residence times (Brauns et al. 2007). WLFs can influence internal nutrient mixing and convert monomictic lakes into polymictic lakes (Zohary and Ostrovsky 2011). At lower water levels, increases in nutrient availability have been observed in previous studies (Coops and Hosper 2002; James and Havens 2005; Chen et al. 2011; Li et al. 2016). Thus, water level management can be considered a potential tool to improve water quality in freshwater ecosystems (Coops and Hosper 2002; Li et al. 2016). Previous studies have shown that shallow lakes are especially sensitive to WLFs and relatively minor changes in water level can translate into large variations in the lake surface area and water volume (Gownarlis et al. 2017; Ren et al. 2019). Furthermore, shallow lake ecosystems may be dramatically impacted when the water level changes between 1 and 2 m (James and Havens 2005).

Given that changes in water level are predicted to occur more frequently in lake ecosystems worldwide, we aimed to (1) investigate the spatial and temporal variations in nutrient parameters related to extreme water levels and (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 lake nutrient dynamics and provide a potential tool for future lake management.

**Materials and methods**

**Study area**

Changhu Lake is the third largest freshwater lake in the Hubei Province in central China, located in the Jianghan Plain of the middle region of the Yangtze River basin (30°22′–30°31′ N, 112°12′–112°30′ E, Figure 1). The lake connects to the Yangtze River through the Sihu Main Channel. The surface area is approximately 140 km² and approximately 18 km wide at its widest zone, with a mean depth of 2.1 m and an elevation of 30–31 m above sea level. 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 mid-spring to mid-autumn.

Changhu Lake plays an important role in flood control, freshwater supply, fisheries and aquaculture, and biodiversity protection in the area. The lake is home to approximately 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 meso-eutrophic due to human activities (i.e. overexploitation, pollution, and habitat destruction) and climate change (Liu et al. 2018b), which causes strong degradation of water quality and biodiversity (Hao et al. 2015; Guo et al. 2017).
Sampling campaigns were implemented at bimonthly intervals from 2014 to 2018 at four sites (Figure 1). Site 1 (S1) was situated at the western part of Changhu Lake, and site 2 (S2) and site 3 (S3) were located in the central region of Changhu Lake. Site 4 (S4) was adjacent to the outlet of Changhu Lake, upstream of the Sihu Main Canal. Two liters of surface water samples were collected at each site with precleaned 5 L plastic buckets and preserved in a portable refrigerator before they were sent to the laboratory for further analysis. A total of 120 (4 sites x 6 months x 5 years) water samples were collected. The nutrient parameters, including total nitrogen (TN), ammonia nitrogen (NH₄-N), total phosphorus (TP), and chemical oxygen demand (COD₉₅), were measured following standard methods described by Greenberg et al. (1992). Data on daily water levels were taken from the Water Resources Bureau of the Hubei Province.

**Sampling and sample analysis**

Extreme water levels are defined as monthly water level anomalies over 1 m in relation to the mean of historical data (James and Havens 2005). Across the whole 5-year time series, we identified one extremely low water level (LWL) event (November 2015 to January 2016) and one extremely high water level (HWL) event (July 2016) in Changhu Lake (Figure 2). With this approach, the collected data were aggregated into three different

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**Figure 1.** Location of Changhu Lake and four sampling sites in Hubei province, central China.
phases: Before (samples before the 2015 LWL), After (samples from the 2015 LWL to the 2016 HWL), and Present (samples from the 2016 HWL to the end of the series).

A multivariate technique, ANOSIM, was applied to examine the significant differences in nutrient parameters (TN, NH$_4$-N, TP, and COD$_{Mn}$) among individual years, months, sites, and different phases related to the extreme water levels. Euclidean distance was calculated after the similarity matrix of the dataset was log(x + 1) transformed. Nonmetric multidimensional scaling (MDS) plots were built to explore the patterns of variations in nutrient parameters. Differences in nutrient parameters among years, months, sites, and water level phases were tested using 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. Pearson correlation coefficients were used to explore the relationships among water levels, wind speed, and nutrients. All statistical analyses were performed using the software packages PRIMER 7.0 (Clarke and Gorley 2015), SPSS 19.0 (SPSS Inc., Chicago, IL, USA), Statistica 10.0 (Statsoft Inc., Tulsa, OK, USA), and CANOCO for Windows 4.5 (ter Braak and Smilauer 2002).

**Results**

**Spatial and temporal variations in nutrient concentrations**

The nutrient parameters of Changhu Lake showed significant interannual variations ($p < 0.05$; Figure 3; Table 1). The highest annual mean concentrations of TN (3.11 ± 0.59 mg/L) and NH$_4$-N (0.94 ± 0.29 mg/L) and the lowest annual mean concentration of COD$_{Mn}$ (3.62 ± 0.82 mg/L) were recorded in 2016, while the highest annual mean concentrations of TP (0.19 ± 0.06 mg/L) and COD$_{Mn}$ (4.85 ± 0.53 mg/L) were observed in 2014. The annual mean concentrations of TN (2.12 ± 0.50 mg/L), NH$_4$-N (0.71 ± 0.20 mg/L), and TP (0.15 ± 0.04 mg/L) were significantly lower ($p < 0.05$) in 2017. The annual mean concentration of COD$_{Mn}$ did not vary significantly between 2016 and 2017 (3.72 ± 0.58 mg/L). Thus, the nutrient concentrations of TN, NH$_4$-N, TP, and COD$_{Mn}$ in 2017 were the lowest of those measured throughout the whole study period.
Monthly variations in nutrient concentrations showed the opposite trend to spatial patterns (Figure 4; Table 2). TN, NH₄-N, and TP had similar monthly variations during the study period. The monthly average 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 July, respectively. No significant differences in the concentrations of TN, NH₄-N, and TP were found between the different years.
months, while the COD$_{\text{Mn}}$ concentration showed the opposite trend. The highest monthly average COD$_{\text{Mn}}$ concentration was detected in January (4.55 ± 0.65 mg/L) and the lowest was measured in September (3.61 ± 0.96 mg/L).

The spatial patterns of the nutrient parameters varied across the sampling sites (Figures 3 and 4; Table 3). The concentrations of TN, NH$_4$-N, and TP were significantly different ($p < 0.001$) between the different sampling sites. At S4, the TN, NH$_4$-N, and TP concentrations were significantly lower than those at other sampling sites, with mean values of 2.02 ± 0.51, 0.61 ± 0.19, and 0.11 ± 0.04 mg/L, respectively. The COD$_{\text{Mn}}$ 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$_{\text{Mn}}$ concentrations were found between the four different sampling sites.

Overall, the nutrient status in Changhu Lake showed a distinct pattern of variation over the study period (Figure 5). The nonmetric multidimensional scaling (MDS) had stress values lower than 0.15, indicating that the ordination patterns of nutrient parameters in Changhu Lake were acceptable. The results of the 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 extreme water levels (Figure 5(a),(c),(d)). Months (global $R = 0.006$, $p = 0.327$) presented an $R$-value close to 0, indicating a high degree of monthly similarity (Figure 5(b)).

### Relationships between nutrient concentrations and water levels

Extreme water levels had different impacts on nutrient concentrations in Changhu Lake (Figure 6). Significant increases in nutrient concentrations were observed during the LWL event. In contrast, the nutrient concentrations exhibited abrupt and significant declines following the HWL event. The concentration of TN was significantly different ($p < 0.001$) between the three phases related to the extreme water levels (Figure 7(a); Table 1). The highest TN was recorded after the LWL event from November 2015 to January 2016 (After), with a mean value of $3.29 \pm 0.55$ mg/L. During the pre-LWL period (Before) and

### Table 2. Mean and standard deviation (SD) for several nutrient parameters investigated in Changhu Lake, and significance results of ANOVA test between 6 months (2014–2018).

| Parameter  | Month       |  |  |  |  |  |
|------------|-------------|---|---|---|---|---|
| TN (mg/L)  | Jan         | 2.61 ± 0.50$^a$ | 2.30 ± 0.66$^a$ | 2.40 ± 0.65$^a$ | 2.66 ± 0.82$^a$ | 2.49 ± 0.45$^a$ | 2.60 ± 0.58$^a$ |
|            | Mar         | 2.66 ± 0.82$^a$ | 2.93 ± 0.71$^a$ | 2.49 ± 0.65$^a$ | 2.76 ± 0.83$^a$ | 2.61 ± 0.58$^a$ | 2.60 ± 0.58$^a$ |
|            | May         | 2.65 ± 0.72$^a$ | 2.57 ± 0.65$^a$ | 2.40 ± 0.65$^a$ | 2.66 ± 0.82$^a$ | 2.49 ± 0.45$^a$ | 2.60 ± 0.58$^a$ |
|            | Jul         | 2.31 ± 0.50$^a$ | 2.30 ± 0.66$^a$ | 2.40 ± 0.65$^a$ | 2.66 ± 0.82$^a$ | 2.49 ± 0.45$^a$ | 2.60 ± 0.58$^a$ |
|            | Sep         | 2.93 ± 0.71$^a$ | 2.49 ± 0.65$^a$ | 2.66 ± 0.82$^a$ | 2.49 ± 0.45$^a$ | 2.60 ± 0.58$^a$ | 2.60 ± 0.58$^a$ |
|            | Nov         | 2.30 ± 0.66$^a$ | 2.40 ± 0.65$^a$ | 2.66 ± 0.82$^a$ | 2.49 ± 0.45$^a$ | 2.60 ± 0.58$^a$ | 2.60 ± 0.58$^a$ |

### Table 3. Mean and standard deviation (SD) for several nutrient parameters investigated in Changhu Lake, and significance results of ANOVA test between the four sites (2014–2018).

| Parameter  | Site         |  |  |  |  |  |
|------------|--------------|---|---|---|---|---|
| TN (mg/L)  | S1           | 2.56 ± 0.56$^a$ | 2.77 ± 0.55$^a$ | 2.61 ± 0.62$^a$ | 2.02 ± 0.51$^b$ |
|            | S2           | 2.56 ± 0.56$^a$ | 2.77 ± 0.55$^a$ | 2.61 ± 0.62$^a$ | 2.02 ± 0.51$^b$ |
|            | S3           | 2.56 ± 0.56$^a$ | 2.77 ± 0.55$^a$ | 2.61 ± 0.62$^a$ | 2.02 ± 0.51$^b$ |
|            | S4           | 2.56 ± 0.56$^a$ | 2.77 ± 0.55$^a$ | 2.61 ± 0.62$^a$ | 2.02 ± 0.51$^b$ |

### Note.

Mean and SD values with different letters (a and b) are statistically significant ($p < 0.05$).
at the end of the time period (Present), the TN was significantly lower than that after the LWL period, with mean values of 2.62 ± 0.48 and 2.28 ± 0.52 mg/L, respectively. The variability in NH₄-N exhibited a trend similar to that of the TN (Figure 7(b); Table 4). The concentration of NH₄-N in the After phase (1.06 ± 0.24 mg/L) was significantly ($p < 0.001$) higher than that in the Before (0.79 ± 0.20 mg/L) and Present (0.74 ± 0.21 mg/L) phases.

Figure 5. Non-metric multidimensional scaling (MDS) plots of nutrient parameters in Changhu Lake for different (a) years, (b) months, (c) sampling sites, and (d) phases related to the extreme water levels. Before, samples from January 2014 to September 2015; After, samples from November 2015 to July 2016; Present, samples from September 2016 to November 2018.

Figure 6. Time series of (a) total nitrogen (TN), (b) ammonia nitrogen (NH₄-N), (c) total phosphorus (TP), and (d) chemical oxygen demand (CODMn) in Changhu Lake. LWL, extremely low water level event; HWL, extremely high water level event.

at the end of the time period (Present), the TN was significantly lower than that after the LWL period, with mean values of 2.62 ± 0.48 and 2.28 ± 0.52 mg/L, respectively. The variability in NH₄-N exhibited a trend similar to that of the TN (Figure 7(b); Table 4). The concentration of NH₄-N in the After phase (1.06 ± 0.24 mg/L) was significantly ($p < 0.001$) higher than that in the Before (0.79 ± 0.20 mg/L) and Present (0.74 ± 0.21 mg/L) phases.

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Figure 6. Time series of (a) total nitrogen (TN), (b) ammonia nitrogen (NH₄-N), (c) total phosphorus (TP), and (d) chemical oxygen demand (CODMn) in Changhu Lake. LWL, extremely low water level event; HWL, extremely high water level event.
No significant differences in NH$_4$-N were found between the Before and Present phases. The concentration of TP in the Present (0.15 ± 0.05 mg/L) phase was significantly ($p < 0.001$) lower than that in the Before (0.18 ± 0.05 mg/L) and After (0.19 ± 0.06 mg/L) phases (Figure 7(c); Table 4). However, TP did not vary significantly between the different phases related to the LWL event. The concentration of COD$_{Mn}$ showed the same pattern as TP, with the lowest value in the Present (3.85 ± 0.80 mg/L) phase (Figure 7(d); Table 4). Despite this, the COD$_{Mn}$ in the After phase (4.31 ± 1.10 mg/L) was significantly ($p < 0.05$) lower than that before the LWL event (4.62 ± 0.69 mg/L).

Our correlation-based principal component analysis (PCA) clearly showed the loading of nutrient parameters during the period before and after the extreme water levels (Figure 8). The first component (PC1) was strongly and negatively correlated with TN, NH$_4$-N, and TP, suggesting a high nutrient load in the Before and After phases. The
second component (PC2) was largely contributed by CODMn and represented a decline in organic matter after the HWL event (Present).

The relationships between water level and nutrient concentrations were complex. The concentration of CODMn was high at the low water level stage, whereas TN, NH4-N, and TP concentrations increased with rising water level (Figure 9). Furthermore, the wind speed had direct and indirect effects on nutrient concentrations in Changhu Lake (Figure 9). At the high water level stage, the wind speed was significantly negatively correlated with TN and NH4-N.

**Discussion**

Fluctuations in 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 (Wantzen...
et al. 2008; Yang et al. 2017; Gownaris et al. 2018). In fact, WLFs can affect nutrient dynamics by altering water residence times (Brauns et al. 2007), vertical mixing regimes (Liu et al. 2012), and water-sediment interface (Rørslett, 1985). 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 in water levels, respectively. This result is consistent with a previous study in Poyang Lake (Liu et al. 2019), suggesting that the water level was an important driver of nutrient variations. This is important because WLFs are likely to be more frequent under predicted future conditions of global warming and freshwater demands (Evtimova and Donohue 2014; Yang et al. 2016; Gownaris et al. 2018).

The nutrient parameters considered in this study showed significant interannual variations. The lake had high nutrient concentrations during 2014–2016 and low nutrient concentrations during 2017–2018. Lake restoration projects, such as the removal of closed aquaculture areas, artificial breeding and release of fish and benthos, cultivation of aquatic macrophytes, and ecological revetment for lake banks, may result in reduced nutrient concentrations and improve lake water quality (Yang et al. 2020). Meanwhile, an extremely high water level event was identified during the second half of 2016, followed by an abrupt decline in nutrient concentrations due to strong dilution effects (Figure 6). This observation suggested that the interannual variations in nutrient concentrations can be affected by both restoration efforts and hydrological changes.

Changhu Lake also showed monthly variations in its nutrient concentrations during the study period, with significant changes in nutrient concentrations observed in November 2015 and September 2016. The present work demonstrated that the monthly changes in nutrient concentrations varied with water level fluctuations. In November 2015, an abrupt increase (e.g. 17–74%) in nutrient concentrations was recorded in correlation with low water levels. After July 2016, however, the nutrient concentrations significantly declined (e.g. 34–48%) following the high water levels. This finding was in accordance with previous results from China’s Poyang Lake (Li et al. 2016; Wang et al. 2021) and some subtropical reservoirs (Yang et al. 2017), which indicated that extreme water levels can lead to significant differences in nutrients due to strong concentration and dilution effects.

The nutrient concentrations in Changhu Lake showed significant spatial variations. Spatially, the nutrient concentrations at the outlet of the lake were different from those at sites located in the western part of the lake. The field survey revealed 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 accounted for approximately 85% of the nutrient loads in Changhu Lake (Yu et al. 2016). Consistent with the previous observations, S4 had the lowest nutrient concentrations and a relatively high COD₅. Such a difference between the two parts of the lake may be attributed to the growth of aquatic plants that could significantly decrease the concentration of nutrients and suspended particles (Tan et al. 2021).

The nutrient concentrations in Changhu Lake varied significantly throughout the study period and were related to the extreme water levels. The lake had an increase in all the nutrient parameters during and/or following the decrease in water levels. This increase may be associated with wind-induced bottom sediment resuspension (James and Havens 2005) and a combination of high precipitation (with a greater nutrient input) and artificial water transfer (Guo 2017), which reduces submerged aquatic vegetation and periphyton that compete for nutrients and boosts the dominance of cyanobacteria. During the After period, the nutrient concentrations remained at high levels due to the stability of
the WLFs. However, during the Present period, a declining trend in nutrient concentrations was observed following the extremely high water level (HWL) event. These results agree with those of Yang et al. (2017), who reported that due to the dilution effect, extreme WLFs can significantly reduce nutrient concentrations.

The nutrient concentrations in Changhu Lake showed strong correlations with water levels. The concentration of COD$_{\text{Mn}}$, increased with declining water level, which indicated that a low water level can increase the concentration of organic pollutants in the water column. Similar results have been obtained in other works where the gradual lowering of water levels also had a negative effect on COD$_{\text{Mn}}$ (Li et al. 2016, 2019). A lower water level may dredge up bottom sediments and decrease the lake water quality by lowering the hydrological connectivity and increasing water flow velocities and wind speeds (James and Havens 2005; Stefanidis and Papastergiadou 2013). However, at the high level stage, nutrients (i.e. TN, NH$_4$-N, and TP) were significantly and positively correlated with water levels (Figure 9(b)). This result was consistent with field observations from China’s largest freshwater lake (Wang et al. 2021), indicating that nutrients are likely to be more frequently exchanged between rivers and lakes under high water levels. Although nutrient concentrations increased with rising water levels, the nutrient concentrations under low water levels were higher than those under high water levels. This phenomenon is consistent with previous works from two large subtropical lakes (Wang et al. 2012, 2021), which suggested that a higher water level also resulted in the dilution of nutrients within the lake. Moreover, during the two stages, the water level showed significant inverse relationships with wind speed. Due to the relatively weak effects of wind speed on nutrients, this study mainly focused on the water level effect in Changhu Lake.

Based on our study, we demonstrated that fluctuations in the water level can affect nutrient dynamics by influencing hydrological conditions and other environmental variables in Changhu Lake. According to the local lake management agency, Changhu Lake is an important source of drinking and irrigation water for the Sihu Basin. The proposed Changhu Dam will be used to control the water flowing into the basin and result in significant changes in the water regimes. As WLFs are likely to become more frequent during the twenty-first century, local managers can focus on the water levels within Changhu Lake to improve the water quality of the lake in the face of human activity and climate change.

**Conclusion**

This study highlights the impacts of extreme water levels on nutrient dynamics 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 variations. Spatially, the nutrient concentrations at the outlet of the lake were significantly different from those at sites in the western part 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. Given that extreme water levels are likely to occur more frequently under future climate change and human activities, our research may be helpful for the conservation and management of Changhu Lake.

**Disclosure statement**

The authors declare no competing interests.
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Data availability statement

The data that support the findings of this study are openly available in figshare at http://doi.org/10.6084/m9.figshare.17213135.

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