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Water quality characteristics of Poyang Lake, China, in response to changes in the water level

Xia Liu, Katrin Teubner and Yuwei Chen

ABSTRACT

As one of the few remaining lakes that are freely connected with the Yangtze River, Poyang Lake exhibits large annual water level (WL) fluctuations. In this study, weekly samples were collected at the north end of Poyang Lake from September 2011 to December 2012, and we investigated the mechanism of limnological responses to fluctuations in the WL. The study covers three seasons that were associated with WL fluctuations ranging from 8 to 19 m. Spearman's rank correlations and multivariate non-metric multidimensional scaling analyses indicated that low and high WL periods differed in a number of water quality characteristics. The low WL period coincided with the non-growing season and was associated with the peak concentrations of nitrogen, the highest turbidity (Turb), and the lowest water temperature. The high WL period was mainly characterized by enhanced chlorophyll *a* concentration. Spearman's rank correlations revealed positive relationships between the WL and the concentrations of NO_3-N and PO_4-P and negative relationships between the WL and the Turb, total nitrogen, total phosphorus, NO_2-N, and NH_4-N concentrations. All results support the conclusion that the large WL fluctuations are the principal drivers for physicochemical variables in this floodplain lake ecosystem.

Key words | chlorophyll *a*, floodplain lake, total and inorganic nutrients, water level fluctuations, Yangtze River

Xia Liu
Yuwei Chen (corresponding author)
Poyang Lake Laboratory for Wetland Ecosystem Research, State Key Laboratory of Lake Science and Environment,
Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences,
Nanjing 210008,
China
E-mail: *ywchen@niglas.ac.cn*

Katrin Teubner
Department of Limnology and Biological Oceanography,
Faculty of Life Sciences, University of Vienna,
Althanstrasse 14,
1090 Vienna,
Austria

INTRODUCTION

The largest freshwater lake in China, Poyang Lake (28°22′–29°45′N, 115°47′–116°45′E), which is downstream of the Yangtze River, has a surface area of 3,283.4 km^2 and an average depth of 8.4 m. The lake is a tributary of the Yangtze River and directly exchanges and interacts with it. The lake–river interactions are complicated by surface discharges into Poyang Lake from five sub-tributaries (the Xiushui, Ganjiang, Fuhe, Xinjiang, and Raohe Rivers) in the Poyang basin and by climate variations in the region. The outcomes of these interactions determine the lake level and its annual and inter-annual variations, the expansion and contraction of the lake area and the droughts and floods in the lake basin.

Currently, the anthropogenic regulation of rivers, such as through the Three Gorges Dam (TGD) Project, have the role of reducing the discharge of the Yangtze River during the flood season and of increasing the river flow in the dry season (Dai *et al.* 2008). Changes in the discharge and water level (WL) of the Yangtze River can change the blocking force of the river on outflows from Poyang Lake (Hu *et al.* 2007) and affect the WL, water storage, and seasonal variations. Zhang *et al.* (2012) reported that the operation of the TGD intensified the extremes of the wet and dry conditions downstream of Poyang Lake, which, in particular, further reduced the WL over the dry period from late summer to autumn. These changes can put serious pressure on communities in the lake basin, e.g., WLs force changes in the water chemistry and biota both directly and indirectly (Van den Brink *et al.* 1994; Coops *et al.* 2003; Zalocar de

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Domitrovic 2003; Wei *et al.* 2016). Noges *et al.* (2003) stressed that increased internal nutrient loading and high levels of chlorophyll *a* (chl *a*) occur during periods of extremely low WL (Mineeva & Litvinov 1998). WL fluctuations from groundwater transport tend to correlate with higher water clarity because of the decrease in inorganic suspended solids, as exemplified by a case study about a lower stretch of a European river, the Rhine (Roozen *et al.* 2003).

Poyang Lake exhibits large annual WL fluctuations, and its WL increases in depth to 19.4 m in August and decreases to 7.9 m in January (Liu *et al.* 2015). Therefore, the main aims of the study are as follows: What is the water environment in the Yangtze River–Poyang Lake system? What is the difference between the high and low WL? What influences would appear in Poyang Lake if the WL of the lake was maintained by a floodgate? The results of this study can be extended to evaluating similar problems in other catchment areas, such as the Dongting Lake to the west of Poyang Lake, and to lake–river systems in other regions and continents.

MATERIALS AND METHODS

Samples were collected weekly over 10 months in the northern part of Poyang Lake from September 2011 to December 2012. The five sampling stations (Figure 1) were located near Xingzi (X1, X2, X3) and Duchang City (D1, D2), which are connected to the Yangtze River and are heavily exploited for commercial activities, particularly for sand excavation and transportation (De Leeuw *et al.* 2010). Ten months with continuous weekly sampling at five stations gives a total of 200 observations. Data for four times a year (winter = January, the low water period; spring = April, the rising water period; summer = July, the high water period; and autumn = October, the falling water period) from January 2009 to October 2012 at X1, X2, and X3 were supplied by the Lake Poyang Laboratory for Wetland Ecosystem Research (PLWER). The WLs in Xingzi and Duchang City fluctuate strongly depending on the stage of the Yangtze River and the amount of precipitation in the catchment area. The WL data were obtained from the website http://www.jxsw.cn.

Measurements of water temperature (WT), pH, specific conductance (Cond), dissolved oxygen, chemical oxygen demand (COD), and turbidity (Turb) were collected at multiple depths at the study sites using a Hydrolab Datasonda 5 Multiprobe (Hach Company, USA). The water transparency (Secchi depth, SD) was determined using a Secchi disk. The water depth was measured using a Speedtech SM-5 Portable Depth Sounder. There was no evidence of thermal stratification in Poyang Lake in 100% of the observations. For indices of light availability in the water column, we used SD values from 2011 to 2012 and also calculated the ratio of the SD to the mixing depth (considered equal to the mean depth due to the polymictic character of the lake). This derived variable directly relates to the frequency of light limitation experienced by the phytoplankton (Reynolds 1984).

The vertically integrated water samples were collected with an acid-cleaned 2 m long and 10 cm diameter plastic tube and kept cool and shaded before transport to the laboratory. The nutrient concentrations, namely, total nitrogen (TN), total phosphorus (TP), ammonium N (NH_4-N), nitrite N (NO_2-N), nitrate N (NO_3-N), and orthophosphate (PO_4-P), were analyzed following the method of APHA (American Public Health Association) (1998). Chl *a* was collected by filtration through GF/F filters (47 mm, Whatman) and measured according to the method described by Lorenzen (1967), with spectrophotometric measurements after extraction in hot 90% ethanol.

All statistical analyses were performed with Statistical Program for Social Sciences (SPSS-IBM, New York, USA) 13.0 software and Sigma-Plot 10.0 (Systat Software, Chicago, IL, USA). Non-metric multidimensional scaling (NMDS) was used to evaluate similarities between stations and between high and low WL conditions. The NMDS was performed using a Bray–Curtis similarity matrix obtained from the log $(x + 1)$ transformed and standardized water quality data.

RESULTS

Temporal changes in hydrological, physical, and chemical variables

During the study period (2011–2012), the WLs of Poyang Lake at Xingzi station varied from 7.8 m to 19.2 m (mean = 14.0 m). The hydrological phases were distinguished as follows: Low A (WL = 7.8–12.1 m; December to April) phases at the beginning of rising and low waters; High

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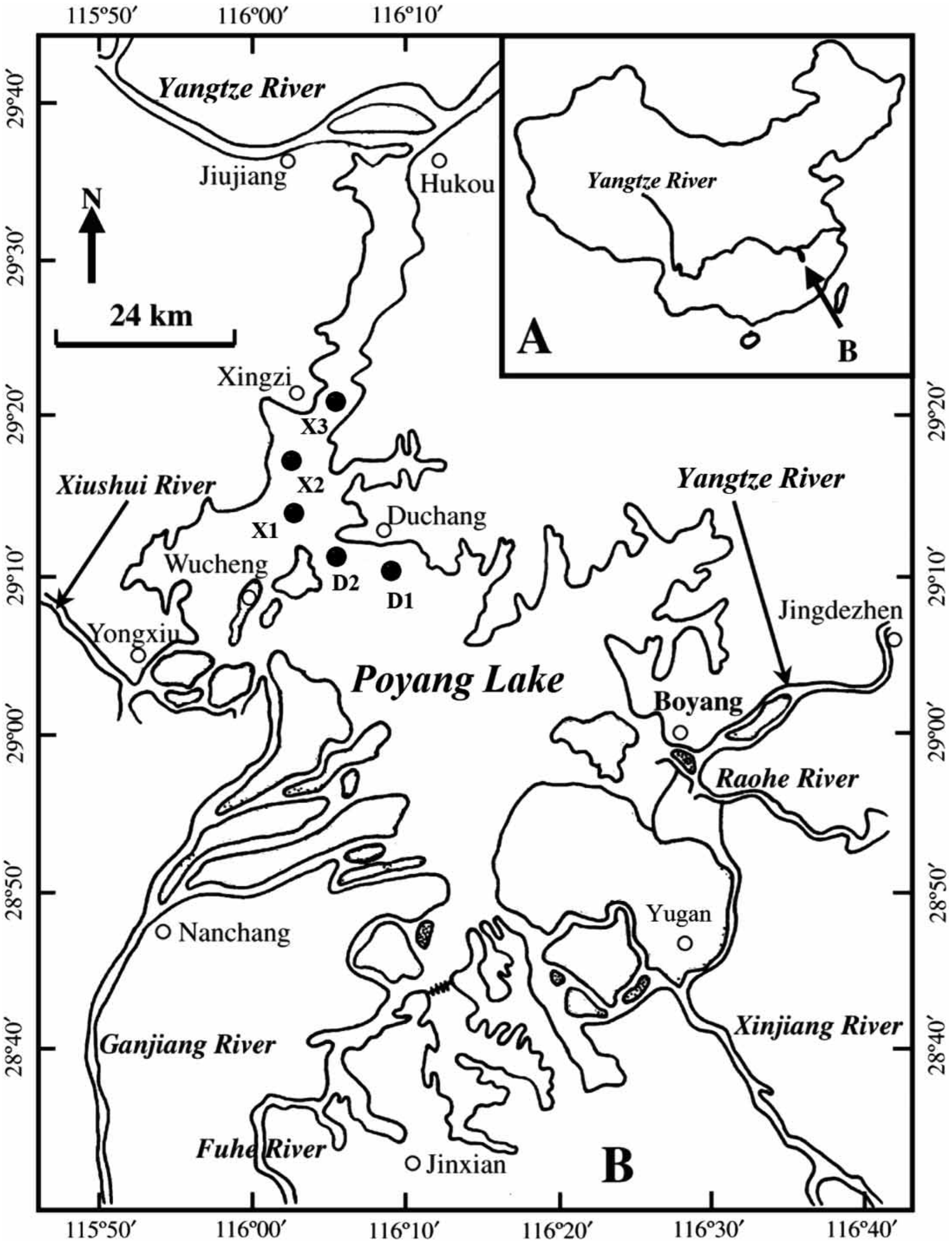

Figure 1 | Location of Poyang Lake, China, and the sampling sites (black dots), revised from Wang *et al.* (2007).

(WL = 15.5–19.2 m; May to September) phases covered the high water phase; Low B (WL = 9.4–14.8 m; September to November) phases covered the beginning of falling and low waters (Figure 2). The WL presented marked variability, being relatively high at the beginning of rising to high waters in 2012 and low during Low A in 2011. This corresponds to a severe drought event in Poyang Lake (2011) (Feng *et al.* 2012). The high WL period coincided with the months in which the temperatures were higher, and the low WL coincided with periods of lower WTs (Figure 2). The WT varied between 5.8 °C in the winter and 32.4 °C in the summer during the study. The mean chl *a* concentrations at the five sampling sites ranged from 1.99 to 17.57 $\mu g\ l^{-1}$. The minimum value of chl *a* was observed in November during the low WL phase, while the maximum average concentration was observed in the high WL phase.

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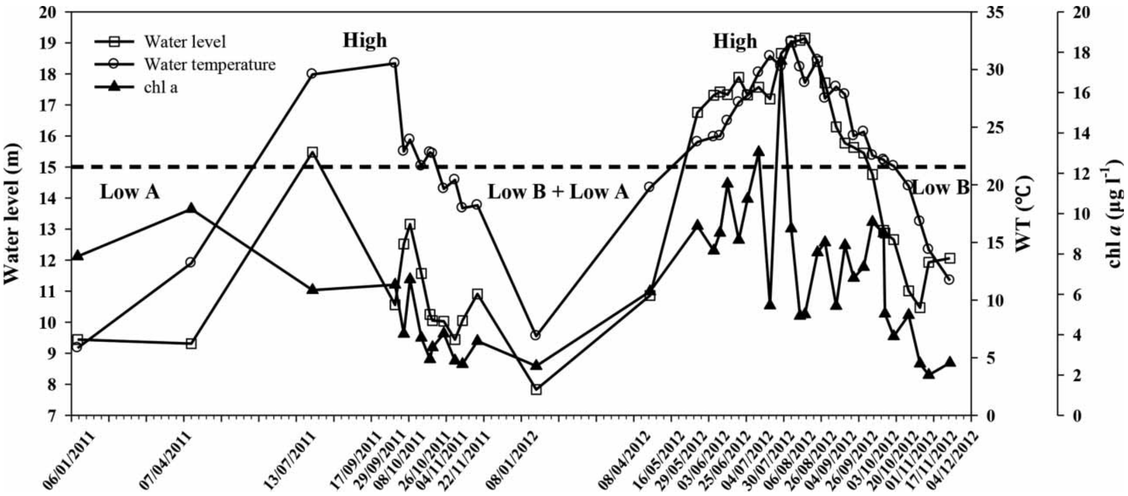

Figure 2 | Seasonal changes in the mean values for the WL, WT, and chl *a* concentrations over the five sampling sites in Poyang Lake, China. The horizontal line represents the point where the WL equals 15 m. The symbols Low A, Low B, and High refer to the periods of low and high water.

The Turb and SD in Poyang Lake showed striking variation in 2011 and 2012 (Figure 3(a)). The mean Turb was 108.7 NTU, with values that ranged between 21.7 NTU and 279.6 NTU. The fluctuations of the SD depended on the Turb of the lake, with the lowest SD generally occurring during periods of high water Turb. The SD slightly increased from 0.25 m at the low WL to 0.35 m during high water periods. There were notable patterns in the SD with mean depth ratios ranging from 0.02 to 0.05 in 2011 and 2012 (Figure 3(b)).

Other nutrient parameters also follow a clear temporal trend from September 2011 to December 2012 in Poyang Lake, and the observed patterns are associated with the fluctuations in the WL as well as with seasonal influences (Figure 4). A clear decrease in the NO_2-N + NO_3-N concentration was observed from the beginning of the rising phase until the high water phase, increasing markedly again in the falling and low water phase. The NH_4-N, TN, and TP concentrations behaved in the same way and were characterized by lower average concentrations in the High WL period and higher average concentrations in the low water periods. The fluctuations in PO_4-P were not pronounced, and the highest PO_4-P concentration was 0.11 mg L^{-1} on September 21, 2011. The NO_2-N + NO_3-N, NH_4-N, TN, and TP concentrations varied significantly on a year scale and also fluctuated with the season, with low values in July (high WL phase) and high values in the low WL phase (Figure 5). The variables related to nutrient concentrations had wide ranges, including NO_2-N + NO_3-N values from 0.12 to 1.32 mg L^{-1}, NH_4-N values from 0.08 to 0.75 mg L^{-1}, TN values from 0.93 to 2.53 mg L^{-1}, and TP values from 0.03 to 0.20 mg L^{-1}. The PO_4-P values had irregular fluctuations in the study period.

The differences in the limnological variables between the low and high WL periods are presented in notched boxplots (Figure 6). The characteristics of the lake water during low and high WLs differ most in the WT values, TN, NH_4-N, NO_2-N, and COD concentrations and also in the chl *a* concentrations. Smaller differences were found in the TP, NO_3-N, and PO_4-P concentrations, Turb values and SD values.

Spearman's rank correlation and the NMDS analysis

The WLs were highly significantly and positively correlated with WTs ($r = 0.78$, $p < 0.0001$, Table 1). The TN, TP, NO_2-N, and NH_4-N concentrations were significantly and negatively correlated with both the WL and WT. The Spearman's rank correlations revealed a positive relationship between the WL and NO_3-N concentration ($r = 0.16$), a positive relationship between the WL and PO_4-P concentration ($r = 0.36$), and a negative relationship between the WL and Turb values ($r = -0.18$). However, no significant correlations

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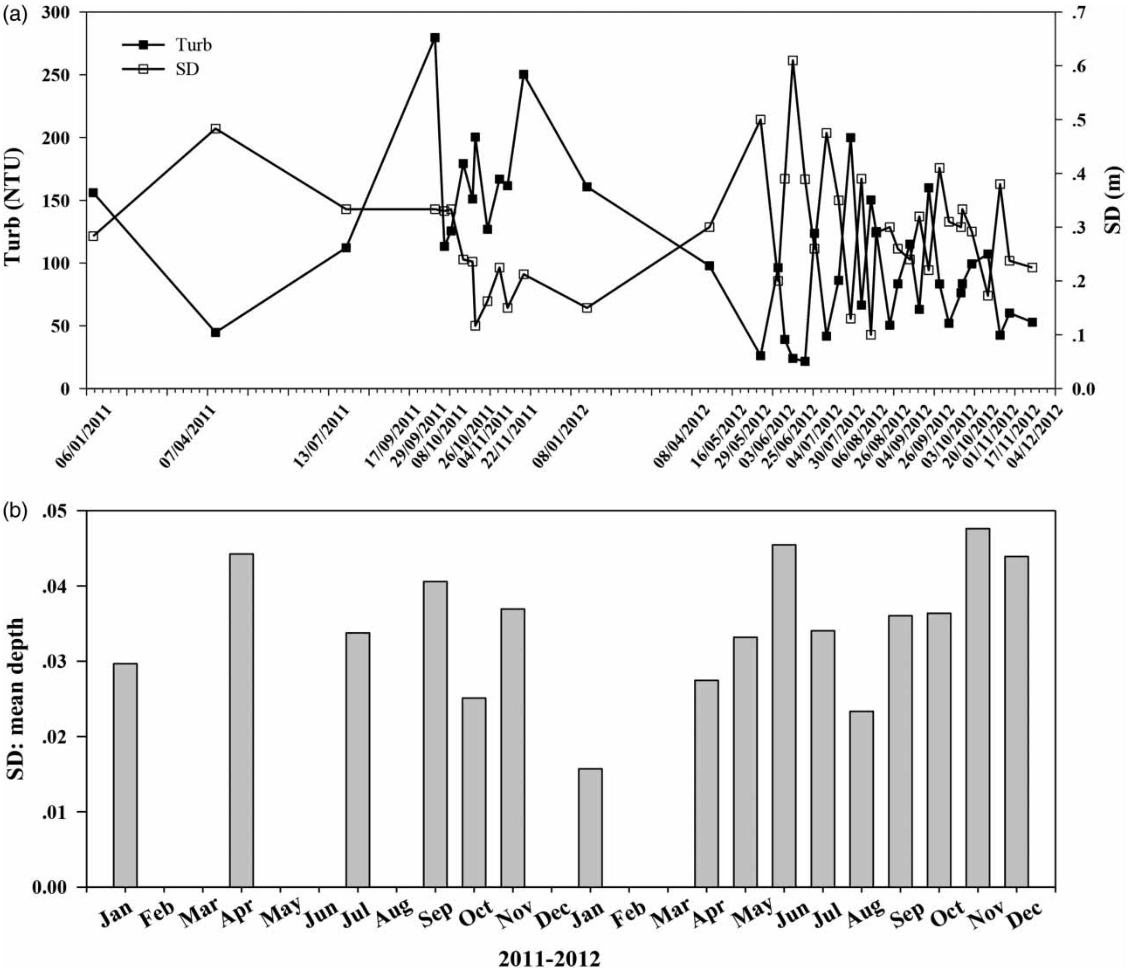

Figure 3 | Seasonal variations in the mean values for (a) Turb and SD from 2011 to 2012 and (b) SD:mean depth ratios from 2011 to 2012 of Poyang Lake, China.

between these variables and the WT were found. Chl *a* concentrations were significantly correlated with optical variables (SD: $r = 0.28$, $p < 0.0001$; Turb: $r = -0.32$, $p < 0.0001$) and nitrogen concentrations (TN: $r = -0.58$, $p < 0.0001$; NO_2-N: $r = -0.36$, $p < 0.0001$; NH_4-N: $r = -0.48$, $p < 0.0001$). A weak but inverse relationship between chl *a* and the TP concentration was found.

The separation of the points for Low A and Low B from High WL indicated differences in the environmental parameters of the water between periods of low and high WL in Poyang Lake (Figure 7). However, the between-site differences were not very strong. The environmental parameters of the water observed in the high WL (SD and chl *a*) were distinct from those observed in the low WLs (NO_2-N, NO_3-N, NH_4-N, and COD).

DISCUSSION

Hydraulic phases

Poyang Lake, located in the floodplain of the Yangtze River, is permanently connected to the main river by a single channel and features a marked seasonal WL pattern, which depends primarily upon the stage of the Yangtze River and the discharge from the Jiangxi basin. The rainy season in southern China begins in April and continues throughout the summer. In most years, discharge from the Jiangxi basin increases through the late spring and peaks during early to mid-summer, raising the level of Poyang Lake, which drains into the Yangtze River at Hukou. From July to early September, the discharge from the Jiangxi basin steadily decreases,

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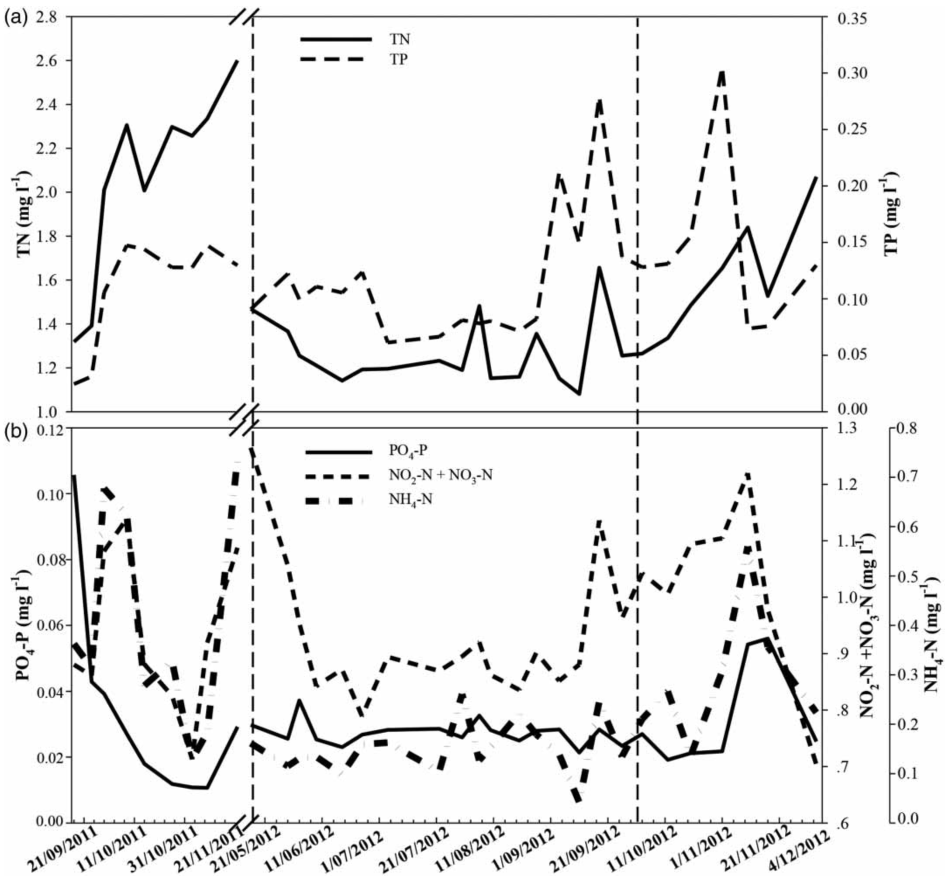

Figure 4 | Seasonal changes in the mean values for (a) TN and TP and (b) total oxidized inorganic N (NO_2-N + NO_3-N), ammonium N (NH_4-N), and phosphate P (PO_4-P) over the five sampling sites in Poyang Lake, China. The vertical dashed lines represent different hydrological phases.

while at the same time, the discharge and WL of the Yangtze River increases. Once the WL of the Yangtze River is higher than that of the lake, the flow of water from the lake into the Yangtze River reverses, and the muddy water from the Yangtze River flows into the lake (Shankman *et al.* 2006, 2009). Poyang Lake is thus naturally flooded during the growing season, and large areas can be dry during the low water season so that this ecosystem represents a type of large wetland (Bayley 1995). This large shallow lake basin exhibits a large annual WL fluctuation, which contrasts with isolated lakes on the middle–lower reaches of the Yangtze floodplain.

Physical and chemical variables in the low and high water seasons

The temporal-scale investigation in Poyang Lake confirmed that its heterogeneity was reflected in the narrower range of optical variables (SD, Turb, and SD:mean depth ratios) we examined (Figure 3). These variables are also highly useful indicators of trophic status and ecosystem health (Bonansea *et al.* 2015). A small decrease in Turb values was thus discovered with high WLs associated with higher SD transparency (Figure 3). The Turb values were thus inversely related to the fluctuations in the WL (Table 1). Evidence of increasing water transparency with a high WL has also been noted for other lakes in river floodplains (De Oliveira & Calheiros 2000; Izaguirre *et al.* 2001). Despite the slight variation in the water transparency throughout the year, which refers to the mean SD for low and high water periods of 0.25 and 0.35 m (Figure 3), Poyang Lake is a turbid lake, and the Turb is the result of many unique factors. First, Poyang Lake is heavily exploited for commercial activities, particularly for sand excavation and transportation in the northern

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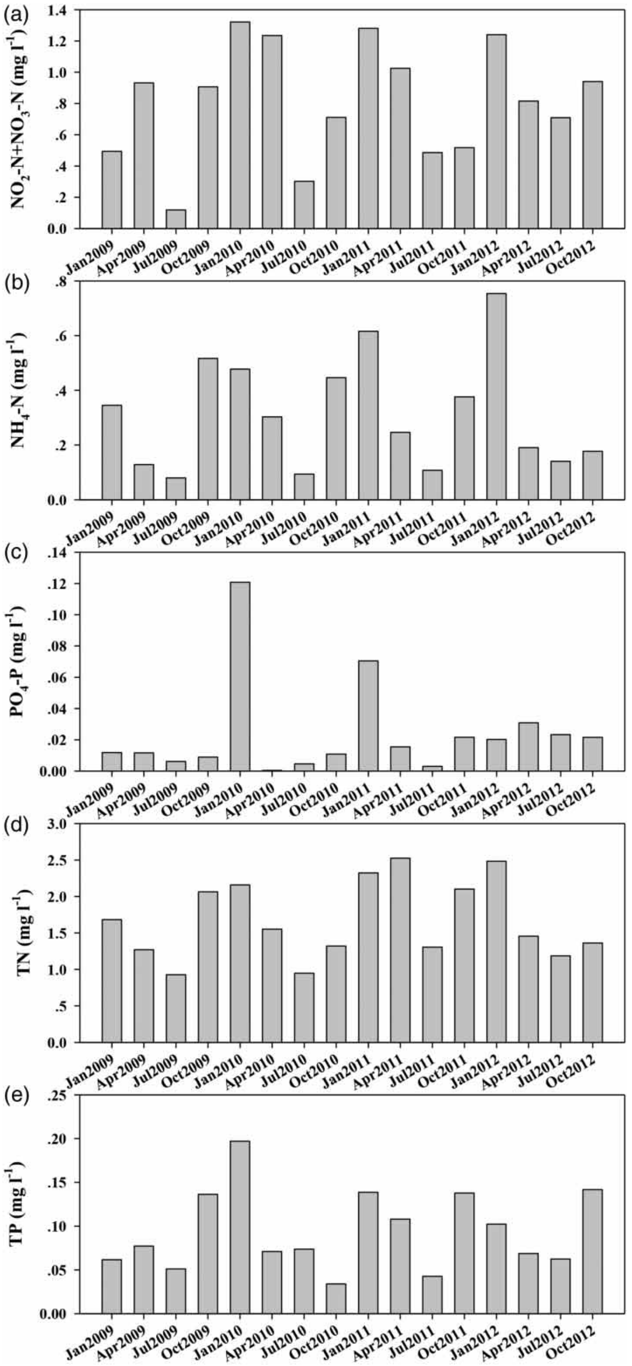

Figure 5 | Variations in nutrient concentrations in Poyang Lake from 2009 to 2012: (a) total oxidized inorganic N (NO_2-N + NO_3-N); (b) ammonium N (NH_4-N); (c) phosphate P (PO_4-P); (d) TN; and (e) TP.

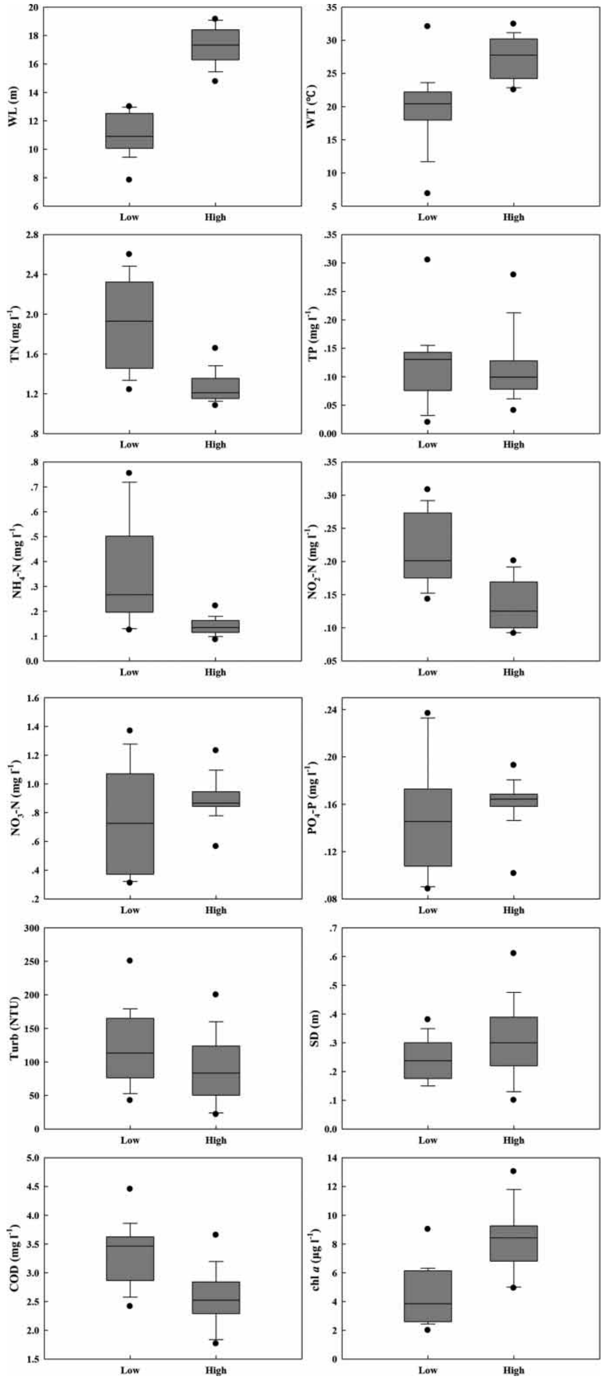

Figure 6 | Box-plots of various limnological parameters in Poyang Lake during low water and high WLs.

region (De Leeuw *et al.* 2010). Second, Poyang Lake, which is connected to the Yangtze River, displays natural river features, particularly in dry seasons. As noted by Zou *et al.* (2011) and Cao *et al.* (2016), the flow rate and, accordingly, the sediment resuspension, is greater during the low water season than in the high water season. It is important

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Table 1 | Spearman's rank of correlation coefficients and *p*-values for the relationships among WT, WL, chl *a* concentration and physicochemical variables in Poyang Lake

	WT (*p*-values)	WL (*p*-values)	Chl *a* (*p*-values)
WT		0.78 (0.00)	0.56 (0.00)
WL	0.78 (0.00)		0.58 (0.00)
chl *a*	0.56 (0.00)	0.58 (0.00)	
Turb	– 0.12 (0.10)	– 0.18 (0.01)	– 0.32 (0.00)
SD	0.07 (0.32)	0.06 (0.40)	0.28 (0.00)
TN	– 0.72 (0.00)	– 0.70 (0.00)	– 0.58 (0.00)
TP	– 0.35 (0.00)	– 0.29 (0.00)	– 0.12 (0.09)
NO_2-N	– 0.49 (0.00)	– 0.64 (0.00)	– 0.36 (0.00)
NO_3-N	– 0.13 (0.08)	0.16 (0.03)	0.11 (0.13)
NH_4-N	– 0.48 (0.00)	– 0.55 (0.00)	– 0.48 (0.00)
PO_4-P	0.07 (0.32)	0.36 (0.00)	0.11 (0.13)

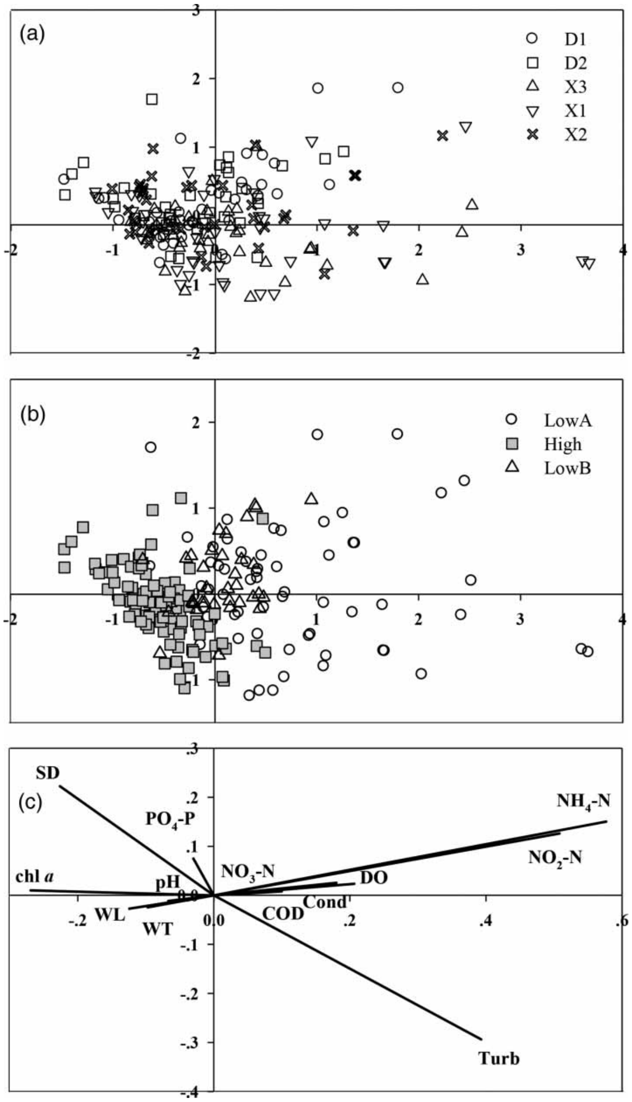

Figure 7 | The results of the NMDS analysis in Poyang Lake, China: (a) different sampling stations; (b) different WLs; and (c) differences in physicochemical parameters among different WLs and different sampling stations. Analyses are based on all values of the five sampling sites.

to note that the SD:mean depth ratios were also very low (<0.05) in Poyang Lake. Under those conditions, light limitation of the phytoplankton is expected to occur in the lake.

All evidence showed a strong seasonal fluctuation in the limnological variables, especially those for nutrients. According to our records, nitrogen did not have the most pronounced concentrations at times of high water discharge but tended to peak during the periods of falling and low water in Poyang Lake (Figures 4 and 5). Our results are in accordance with an earlier short-term observation of 33 shallow lakes in the middle and lower reaches of the Yangtze River by Wu *et al.* (2006), which also included Poyang Lake. They indicated that the concentrations of TN, nitrate, and ammonia were, on average, approximately two to three times higher during the winter season (low water period) than the growing season (high water period). This phenomenon of elevated nitrogen concentrations during the low water period and vice versa is also known from other lentic water bodies, which are temporarily hydrologically connected with the main channel of a large river (Train & Rodrigues 1998; Tockner *et al.* 1999; De Oliveira & Calheiros 2000). There are several mechanisms that could lead to higher nutrient levels of nitrogen during low water periods in Poyang Lake, including greater sediment resuspension, the oxidation of exposed sediments in the floodplain with released nutrients being transported to the lake, simple concentration of the nutrients in a smaller volume of water, and increased water residence time leading to the accumulation of nutrients. Phosphorus was also influenced by fluctuations in the WL according to our results (Table 1). However, the intra-annual variations in PO_4-P and TP were not pronounced and were similar throughout the study, with slightly enhanced concentrations during the low water season (Figures 4 and 5). The rather even seasonal distribution of the phosphorus again confirms the previous measurements for lakes in the floodplain of the Yangtze River by Wu *et al.* (2006).

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Spearman's rank correlation analysis

The negative relationship of chl *a* with Turb suggests an important role of light limitation in Poyang Lake (Table 1). This result has been previously documented (Figure 3). The positive relationship of chl *a* with SD indicates that factors other than phytoplankton biomass (such as the sand mining and resuspended sediment) are driving SD and that the phytoplankton increase in biomass when those other factors are relatively low.

Negative correlations were observed between the chl *a* concentrations and nitrogen concentrations (Table 1). Such inverse relationships between the chl *a* concentration and nitrogen concentrations are not common. With the increasing awareness of eutrophication in many lakes across the globe, models have been developed to predict the response of ecosystems to anthropogenic changes in nutrient enrichment (Carlson 1977; Forsberg & Ryding 1980; OECD 1982; Dokulil *et al.* 2000). Most of these models are similar in that they predict the algal biomass as it peaks during the growing season, which corresponds to elevated concentrations of the total pool of phosphorus and nitrogen. These models mainly cover permanent lentic lakes and assume that a substantial proportion of the total nutrient pools will be immediately available for algal growth and are thus allocated to the phytoplankton biomass. The lack of such a seasonal coherence between the total nutrient pools (TN and TP) and the algal biomass becomes evident for Poyang Lake when considering the peak season for the concentrations of nitrogen (elevated nitrate concentrations during the low water period in the winter season) and of phytoplankton development (the chl *a* maximum during the high water period, which coincides with the growing season) (Figure 2, Table 1). This time lag might be explained by the findings of Tockner *et al.* (1999), who measured the exchange of organic matter and nutrients in the floodplain of the Danube River. According to their study, a floodplain acts as a major sink for suspended sediments associated with a considerably high amount of nitrate-N and as a source for dissolved organic carbon and algal biomass. The elevated concentrations of TN and specific species of nitrogen in Poyang Lake during the low water period and vice versa found in our study might therefore be allocated to an ecosystem response, with a time lag between retaining (sedimentation at low water periods) and remobilizing (algal growth during high water periods) the nutrients in the floodplain. Facing the recent eutrophication of lakes in China, as reported for 84% of 103 lakes studied by Liu *et al.* (2010), a current trend of further nutrient enrichment in such a large floodplain system such as the Poyang Lake might be expected. Lag effects of the degradation of organic matter (Bayley 1995) due to the alternating of flooding and draw down might become even more pronounced if the lake continues to receive additional nutrients from municipal waste and farming activities. According to Tockner *et al.* (1999), as mentioned before, the processes of accumulating nutrients in a floodplain can be counterbalanced by the relocation of nutrients via their incorporation into the algal biomass and their drift into the main river channel. Algae can thus play an important role in remobilizing the nutrient pool retained in Poyang Lake.

Implications for the operation of the Poyang floodgate

According to the authorities of the Jiangxi government, the proposed Poyang floodgate will only be used to hold back water normally returning to the Yangtze River during the dry season (Li 2011). This policy reveals a scenario of applying floodgate storage to maintain water resources in Poyang Lake when the WLs would normally be decreasing. In this case, the residence time of water in Poyang Lake would be prolonged, flow rates in the lake would be lowered, and water transparency might also be elevated. The lentic conditions diminish the potential effects of nutrients washing out of Poyang Lake. Consequently, high nutrient concentrations coupled with high water transparency may have the effect of increasing the biomass of phytoplankton in Poyang Lake.

CONCLUSIONS

The WL in Poyang Lake ranged from approximately 8 to 19 m during our study. These large WL fluctuations seemed to be the principal driver for physical and chemical variables in this ecosystem, which are mainly characterized by an enhanced pool of nitrogen associated with the highest

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Turb during the low water period. The many correlations related to the seasonal phytoplankton development, such as the inverse relationship between chl *a* and nitrogen and the co-variation between chl *a* and SD water transparency, may be related to the nature of this naturally flooded ecosystem. These findings strongly underpin the need to develop a specific assessment for this large floodplain lake because the seasonal development of water transparency and nutrient dynamics in Poyang Lake differs in principle from what is commonly found for permanent lentic systems. Additionally, our study provides baseline data for a future assessment of ecological change.

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