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Periodically hydrologic alterations decouple the relationships between physicochemical variables and chlorophyll-*a* in a dam-induced urban lake

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ABSTRACT

Periodically hydrologic alterations driven by seasonal change and water storage capacity management strongly modify physicochemical properties and chlorophyll-*a* (Chl-*a*) and their interactions in dam-induced lakes. However, the extent and magnitude of these changes still remain unclear. This study aimed to determine the effects of periodically hydrologic alterations on physicochemical variables and Chl-*a* in the dam-induced urban Hanfeng Lake, upstream of Three Gorges Reservoir. Shifts in Chl-*a* and 13 physicochemical variables were recorded monthly in the lake from January 2013 to December 2014. Chl-*a* was neither seasonal nor inter-annual differences while a few physical variables such as flow velocity (V) exhibited significantly seasonal variabilities, and chemical variables like total nitrogen (TN), nitrate-nitrogen (NO_3-N), total phosphorus (TP), dissolved silica (DSi) were markedly inter-annual differences. Higher TN:TP (40:1) and lower NO_3-N:DSi (0.8:1) relative to balanced stoichiometric ratios suggested changes in composition of phytoplankton communities and potentially increased proportion of diatom in Hanfeng Lake. Chl-*a* was predicable by combination of dissolved oxygen (DO), TN and DSi in dry season, and by V alone in wet season. During the whole study period, Chl-*a* was solely negatively correlated with TN:TP, indicating decline in N concentration and increase in P could therefore increase Chl-*a*. Our results highlight pronounced decoupling of linkages between Chl-*a* and physicochemical variables affected by periodically hydrologic alterations in dam-induced aquatic systems.

Introduction

Dam-induced lake and/or reservoir system usually experience periodically hydrologic alterations (Yang et al., 2008; Benjankar et al., 2012), resulting in frequent fluctuations in water level (Pinter and Heine, 2005; Wang et al., 2018). Consequently, changes in water level were documented to play crucial roles as intermediate disturbance in regulating the physical, chemical and biotic shifts in lacustrine ecosystems (Chow-Fraser, 2005; Naselli-Flores and Barone, 2005). White et al. (2008) found that water level changes were significantly correlated with water quality while only affected markedly macroinvertebrates among biotic indicators. Yang et al. (2016) reported that decline in water level increased dissolved oxygen (DO), total phosphorus (TP) and phytoplankton biomass, but reduced total nitrogen (TN) and N:P ratio in subtropical reservoirs. Though great efforts have been made to obtain ecosystem responses to water level changes

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(Coops et al., 2003; Leira and Cantonati, 2008), more data are emphatically needed for understanding the relationships between water level changes and indicators of aquatic ecosystem disturbed by hydrologic alterations considering the anticipated increasing in frequency and intensity of human activities and changing climate.

In addition to effects of hydrologic alterations on changes in aquatic ecosystem, a major attention has been also paid to the relationships between physicochemical variables and chlorophyll-*a* (Chl-*a*) in aquatic systems. Rakocevic-Nedovic and Hollert (2005) established a prediction for Chl-*a* involved secchi depth, DO, TP and TN based on log-transformed scales in a subtropical lake. Wu et al. (2006) fitted separately the relationships between Chl-*a* and inorganic nitrogen and TP as well as TN:TP given seasonal variability. In recent years, many studies proved that non-linear models were better fit for relationships between TP and Chl-*a*, and TN:TP strongly affected the prediction of Chl-*a* with TP (McCauley et al., 1989; Watson et al., 1992). Similar to that, Filstrup and Downing (2017) further explained the relationships between Chl-*a* and TP as well as TN under extreme nutrient regimes. However, effects of intensely hydrologic alterations on prediction of Chl-*a* with physicochemical variables still remain poorly understood. Indeed, understanding these relationships will help to make decisions on water quality management of lake systems under the heightened human activities and climate change.

Hanfeng Lake, a dam-induced urban lake, was constructed upstream backwater zone of the Three Gorges Reservoir (TGR). As its initially designed aim to reduce the area of water fluctuating zone (from 24 to 3.06 km^2), Hanfeng Lake is subjected to periodical water releasing and river flow recharge in wet season and backflows from TGR in dry season (Qin et al., 2012). Hence, large fluctuations of water level are frequently found intra- and inter-annually in this dam-induced lake, which was opposite to natural lakes. Moreover, some qualitative and quantitative features such as maximum depth and hydrodynamics are significantly different between the dam-induced and natural water bodies (Straškraba et al., 1993). Previous studies implemented in Hanfeng lake have mainly concentrated on its effects on the regulation of water fluctuating zone and changes in water quality (Chen et al., 2018a), and detecting the variability in water resources allocation and eutrophic status in relation with their influence factors driven by hydrologic alterations (Chen et al., 2018b; Yang et al., 2017). Nevertheless, little information is available on the effects of hydrologic alteration on the linkages between physicochemical variables and Chl-*a* concentration. Given the key role of Chl-*a* concentration in indication of phytoplankton biomass and water quality, understanding the changes in water physicochemical properties and Chl-*a* will contributes importantly for making optimal strategies for improving sustainable development of water resources management in the area of TGR.

The specific objectives of this study therefore are to (1) determine the effects of periodically hydrologic alterations on changes in physicochemical properties and Chl-*a* concentration, (2) examine the potential relationships among these variables, and (3) identify the closest indicators linking Chl-*a* concentration in the dam-induced Hanfeng Lake.

1. Methods

1.1. *Study area*

The Hanfeng Lake (108.42° E, 31.18° N) is located in the Fengyue Town, Kaizhou District, Chongqing Municipality, China (Fig. 1). It controls an upper catchment with an area of approximately 3199 km^2, and has normally a surface area of 14.8 km^2 and a water storage capacity of 80 million m^3. Hanfeng Lake has an average annual runoff discharge of around 2.4 billion m^3 which are mainly sourced from Dong River (37%), Nan River (28%), Taoxi River (28%), Toudao River (2.5%) and others (4.5%), making it the largest urban artificial lake in the western interior of China (Chen et al., 2018a). The local climate pertains to typical subtropical humid monsoon with a mean annual temperature of 18.5 °C. Average annual rainfall is 1385 mm with about 75% occurring during the wet season from May to September (Qin et al., 2012).

The flow discharge of the Hanfeng Lake is periodically impacted by the upper river flows, water releasing from the dam and backflows from TGR. Therefore, hydrographic features of the Hanfeng Lake showed periodically intra- and inter-annual shifts. The theoretically regulated water level was not achieved during study period, however, the observed water level in TGR and in front of dam were comparatively showed the differences on water level fluctuations between TGR and Hanfeng Lake (Fig. 2). From October to January, Hanfeng Lake was characterized by high water level, wide surface area and low flow velocity as a result of the backflows from TGR, showing the similar condition with the natural lake. During February-April, decreased water level and surface area were observed because of the sound influence by the water level decline in TGR, which led to widely bare lakeshores in the lake. In contrast, it was markedly impacted by the water releasing from the dam and the rainfall-runoff replenishment occurring from May to August in the Hanfeng Lake. In September, the backflows from TGR gradually recharge the lake, resulting in increase of water level. Consequently, the May to September corresponded to wet season, and October to April served to dry season in this study.

1.2. *Water samples and measurements*

A total of 5 sampling sites were used to represent the spatial characteristics of the Hanfeng Lake in this study (Fig. 1). Among them, site 1 was located at the downstream of the dam gate; site 2 was situated at the central part of main water body; sites 3, 4 and 5 were located at the mouths of Dong River, Toudao River and Nan River, respectively. Sampling for each site was conducted monthly (weekly in May and October) from January 2013 to December 2014. At each site, water depth (WD) was recorded by the measuring tape with a range of 50 m and flow velocity (V) was measured using portable current meter (LGY, NS, China). Additionally, water temperature (T), pH, dissolved oxygen (DO) and Chl-*a* were measured using a portable multi-parameter meter (Minisonde5x, Hach, USA).

In situ, water samples were collected using a 2.5 L grab sampler under different conditions of WD: when WD was lower than 5 m, water samples were collected only at 0.5 m located below the water surface (top layer); when WD was greater than 5 m and lower than 10 m, water samples were collected at top layer and at half of the water depth (middle layer); when WD was deeper than 10 m, water samples were collected at top layer, middle layer and at 0.5 m located above the lakebed (bottom layer), respectively. This caused that only top layer water samples were collected from March through August, while water samples at all three layers were collected from September through February due to periodical evolution of hydrograph in the Hanfeng Lake. The grabbed water samples were filled into duplicate polyethylene bottles (~500 mL) which had been pre-washed with lake water corresponded to sampling depths. After that, these samples were kept in the dark at 4 °C, until being processed immediately on return to the laboratory within 24 hr.

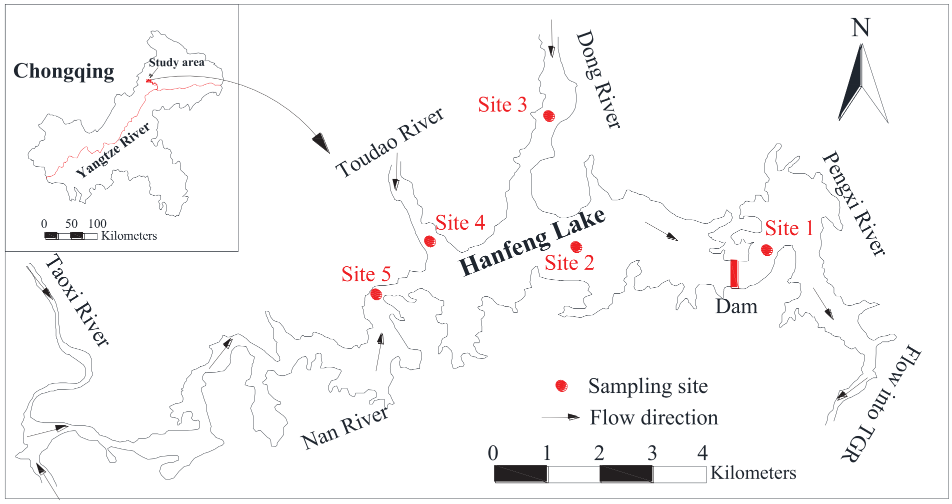

Fig. 1 – Location map of study area showing the distribution of sampling sites. TGR, Three Gorges Reservoir.

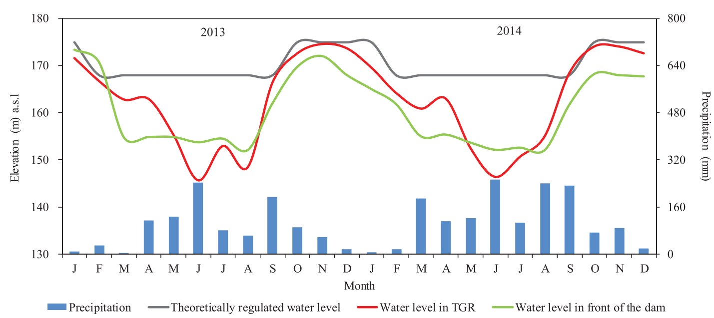

Fig. 2 – Monthly changes in precipitation, theoretically regulated water level of Hanfeng Lake, water level in TGR and water level in front of the dam.

In laboratory, one bottle of water samples was filtered through 0.45 μm glass microporous fiber membrane. Dissolved silica (DSi) was analyzed spectrophotometrically using the blue ammoniummolybdate reaction (Mullin and Riley, 1955; Tallberg et al., 1997), which has been demonstrated to be high sensitivity and accuracy for determination of soluble silicon in freshwater (Tang et al., 2014). Ammonium-nitrogen (NH_4-N) and nitrate-nitrogen (NO_3-N) were determined spectrophotometrically using indophenol blue method and sulfamic acid method, respectively. The other bottle of water samples was unfiltered and total nitrogen (TN) was measured spectrophotometrically by digestion with the addition of alkaline potassium peroxodisuphate. Total phosphorus (TP) was measured using molybdenum blue colorimetric method after addition of potassium peroxodisuphate. The measurements for above indicators (i.e. NH_4-N, NO_3-N, TN, TP) were conducted in accordance with the standard Chinese protocols (SEPA, 2002). The descriptive statistics on abovementioned water variables dataset from January 2013 to December 2014 were summarized in Appendix A Table S1. Water variables measured weekly in May and October were averaged to represent the monthly changes in this study. Accordingly, the changes in physicochemical properties and Chl-*a* concentration affected by periodically hydrologic alterations were interpreted in terms of 2-year monthly monitoring in water environmental condition.

1.3. *Statistical analysis*

Kruskal-Wallis H test was used to preferentially examine the differences on variables among sampling depths and also among sampling sites. As a result, it showed that three water layers exhibited no significant differences on most variables from September to February (Appendix A Table S2), except T in December 2013, Chl-*a* in January 2014, TN and TP in February 2014 and NH_4-N in September 2014. The five sampling sites also presented insignificant differences on most variables in both 2013 and 2014, except TP in 2014 (Appendix A Table S3). Accordingly, the average value for each variable calculated from 5 sampling sites at the top layer were employed for the following analyses. Manny-Whitney U test was performed to compare the differences on variables between sampling years and between the wet and dry seasons. Spearman's rank correlation analysis was carried out to unravel the correlations among study variables. The forward stepwise regression analysis (FSRA) was adopted to explore the independent physicochemical variables that were influencing Chl-*a* concentrations in different periods when the collinearity occurred among those variables (Roach and Grimm, 2009). All variables were log-transformed (base 10) aforehand. For an obtained regression model, only the variables found to be significantly linked to Chl-*a* concentration were included. Coefficient of determination (R^2) explained by the regression variables was also calculated. A *P*-value less than 0.05 was considered statistically

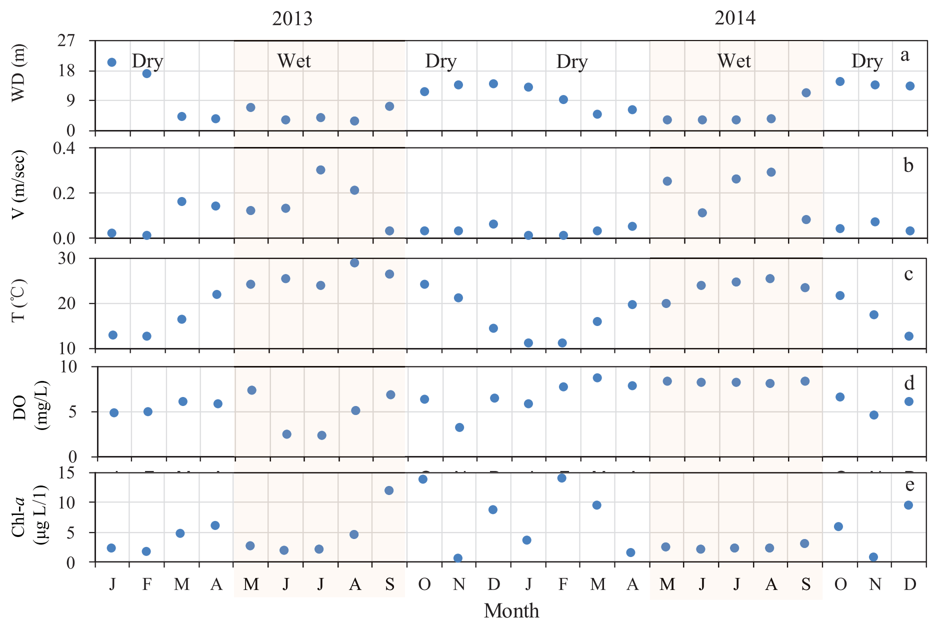

Fig. 3 – Seasonal variations of water depth (WD) (a), velocity (V) (b), temperature (T) (c), dissolved oxygen (DO) (d) and chlorophyll *a* (Chl-*a*) (e) in the Hanfeng Lake during 2013–2014.

significant. Statistical analyses were performed using SPSS 22.0 (IBM, Armonk, New York, USA).

2. Results

2.1. *Variations in physical variables and Chl-*a

During 2013–2014, WD varied from 2.79 (Aug 2013) to 20.4 m (Jan 2013) with an average of 8.5 ± 5.33 m; V ranged between 0.01 (Feb 2014) and 0.30 m/sec (Jul 2013) with an average of 0.1 ± 0.09 m/sec (Fig. 3a, b). T was the lowest in Jan 2014 (11.05 °C) and the highest in Aug 2013 (29.02 °C), averaging 20 ± 5.41 °C (Fig. 3c). DO concentration was the lowest in Jul 2013 (2.38 mg/L) and the highest in Mar 2014 (8.71 mg/L), averaging 6.27 ± 1.85 mg/L (Fig. 3d). Chl-*a* ranged between 0.70 (Nov 2013) and 13.92 μg/L (Feb 2014) with an average of 4.93 ± 4.07 μg/L (Fig. 3e). WD, V and Chl-*a* were not statistically significant difference between 2013 and 2014, T was significant higher in 2013 than in 2014 and DO presented opposite trend with T (Fig. 4).

Seasonally, WD was significantly higher in dry (11.24 ± 5.06 m) season than in wet (4.68 ± 2.79 m) season, while the opposite trend was true for both V and T (dry: 0.05 ± 0.05 m/sec and 16.69 ± 4.44 °C; wet: 0.18 ± 0.09 m/sec and 24.64 ± 2.32 °C) (Table 1). DO was not significant difference between dry (6.09 ± 1.42 mg/L) and wet (6.52 ± 2.38 mg/L) seasons (Table 1). Chl-*a* showed no significant difference between dry (5.89 ± 4.55 μg/L) and wet (3.58 ± 3.00 μg/L) seasons (Table 1).

2.2. *Variations in chemical variables*

During 2013–2014, pH varied from 7.12 (Apr 2013) to 9.20 (Jul 2013) with an average of 8.19 ± 0.64 (Fig. 5a). TN concentration ranged from 1.05 (Dec 2014) to 3.51 mg/L (Apr 2014) with an average of 1.96 ± 0.72 mg/L (Fig. 5b). NH_4-N concentration varied from 0.02 (Jul 2014) to 0.54 mg/L (Apr 2014) with an average of 0.21 ± 0.16 mg/L (Fig. 5c). NO_3-N concentration varied between 0.15 (Jun 2013) and 1.97 mg/L (Apr 2014) with an average of 0.96 ± 0.53 mg/L (Fig. 5d). TP concentration ranged between 0.05 (Feb 2013) and 0.33 mg/L (Mar 2014) with an average of 0.14 ± 0.07 mg/L (Fig. 5e). DSi varied between 0.07 (Feb 2014) and 4.49 mg/L (Apr 2013) with an average of 1.73 ± 1.38 mg/L (Fig. 5f). TN:TP ratio was the lowest in Apr 2013 (13.88) and highest in Jan 2013 (76.56), averaging 39.88 ± 16.88 (Fig. 5g). NO_3-N:DSi ratio was the lowest in Jun 2013 (0.03) and highest in Mar 2014 (3.49), averaging 0.78 ± 0.86 (Fig. 5h). pH, NH_4-N and TN:TP did not differ significantly between 2013 and 2014, and TN, NO_3-N, TP and NO_3-N:DSi ratio were significant lower in 2013 than in 2014, while DSi concentration was higher in 2013 than in 2014 (Fig. 6).

Seasonal changes in pH, TN, NO_3-N, TP, DSi concentrations and NO_3-N:DSi and TN:TP ratios were not statistically significant differences between dry and wet seasons, while NH_4-N concentration was seasonally higher in dry season (0.27 ± 0.17 mg/L) than in wet season (0.11 ± 0.09 mg/L) (Table 1).

2.3. *Relationships between Chl-*a *and physicochemical variables*

Spearman's rank correlation analysis showed that Chl-*a* was correlated positively with DO (R^2 = 0.66, $P < 0.05$) in dry season and negatively with TN:TP (R^2=0.42, $P < 0.05$) in the whole period, but there was no significant relationship with any physicochemical variables in wet season (Appendix A Table S4). However, some collinearity was found among those variables, such as the positive relationships between TP and pH and DO in dry season (Appendix A Table S4). Hence, FSRA was used to identify the potentially independent physicochemical variables linked to Chl-*a* concentration. Chl-*a* was able to be predicted collectively by DO, TN and DSi with the explanatory variance of 96.4% ($P < 0.01$) in dry season, and only by V with the explanatory information of 50.2% ($P < 0.05$) in wet season, and alone by TN:TP with explanatory 16.9% ($P < 0.05$) in variance in the whole period, respectively (Table 2).

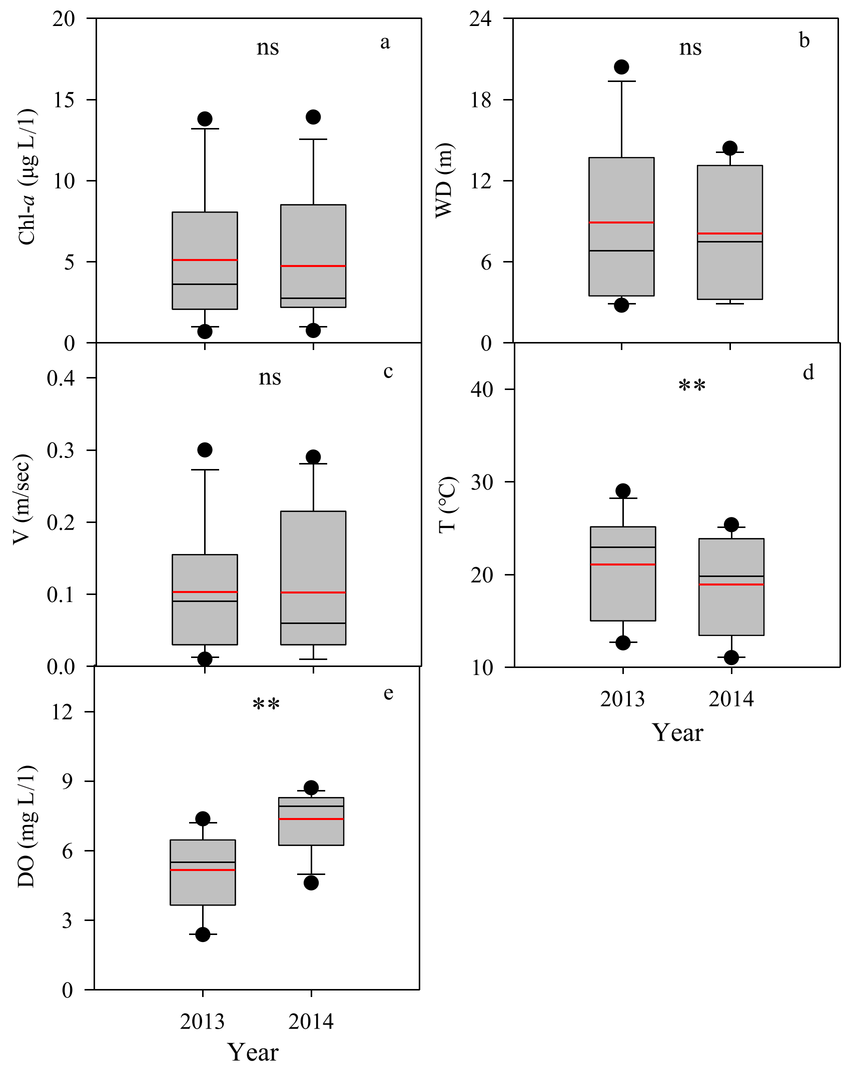

Fig. 4 – Boxplots showing the differences on Chl-*a* and physical variables between 2013 and 2014 in the Hanfeng Lake. (a) Chl-*a*, (b) water depth, WD, (c) V, (d) T, (e) pH and (f) DO. Symbols of boxplot represented as follows: Mean data are red lines, Median data are black lines, 25th and 75th percentiles data are lower and upper edges, 10th and 90th percentiles are lower and upper bars and < 10th and > 90th percentiles data are lower and upper dots outside, respectively. **, the significance at *P*<0.05; ns, not significant.

Table. 1 – Mann-Whitney U test showing the differences between dry and wet seasons in the Hanfeng Lake during 2013–2014.

Season	Index	Chl-*a*	WD	V	T	DO	pH	TN	NH_4-N	NO_3-N	TP	DSi	TN:TP	NO_3-N:DSi
Dry	N	14	14	14	14	14	14	14	14	14	14	14	14	14
	Min	0.70	3.45	0.01	11.05	3.25	7.12	1.05	0.04	0.20	0.05	0.07	13.88	0.05
	Max	13.92	20.40	0.16	24.24	8.71	9.07	3.51	0.54	1.97	0.33	4.49	76.56	3.49
	Mean	5.89	11.24	0.05	16.69	6.09	8.13	1.89	0.27	0.91	0.13	1.55	40.92	0.88
	Std	4.55	5.06	0.05	4.44	1.42	0.58	0.81	0.17	0.48	0.07	1.65	20.18	0.91
Wet	N	10	10	10	10	10	10	10	10	10	10	10	10	10
	Min	2.03	2.79	0.03	19.87	2.38	7.33	1.07	0.02	0.15	0.07	0.21	18.00	0.03
	Max	11.85	11.26	0.30	29.02	8.31	9.20	2.80	0.32	1.69	0.26	3.17	55.62	2.54
	Mean	3.58	4.68	0.18	24.64	6.52	8.26	2.05	0.11	1.02	0.15	1.99	38.44	0.64
	Std	3.00	2.79	0.09	2.32	2.38	0.76	0.61	0.09	0.61	0.06	0.90	11.68	0.82
Significant level	0.380	0.001	0.001	0.000	0.219	0.578	0.464	0.016	0.639	0.429	0.266	0.861	0.242	

Bold value represents the significance at *P*<0.05. N, sample size.

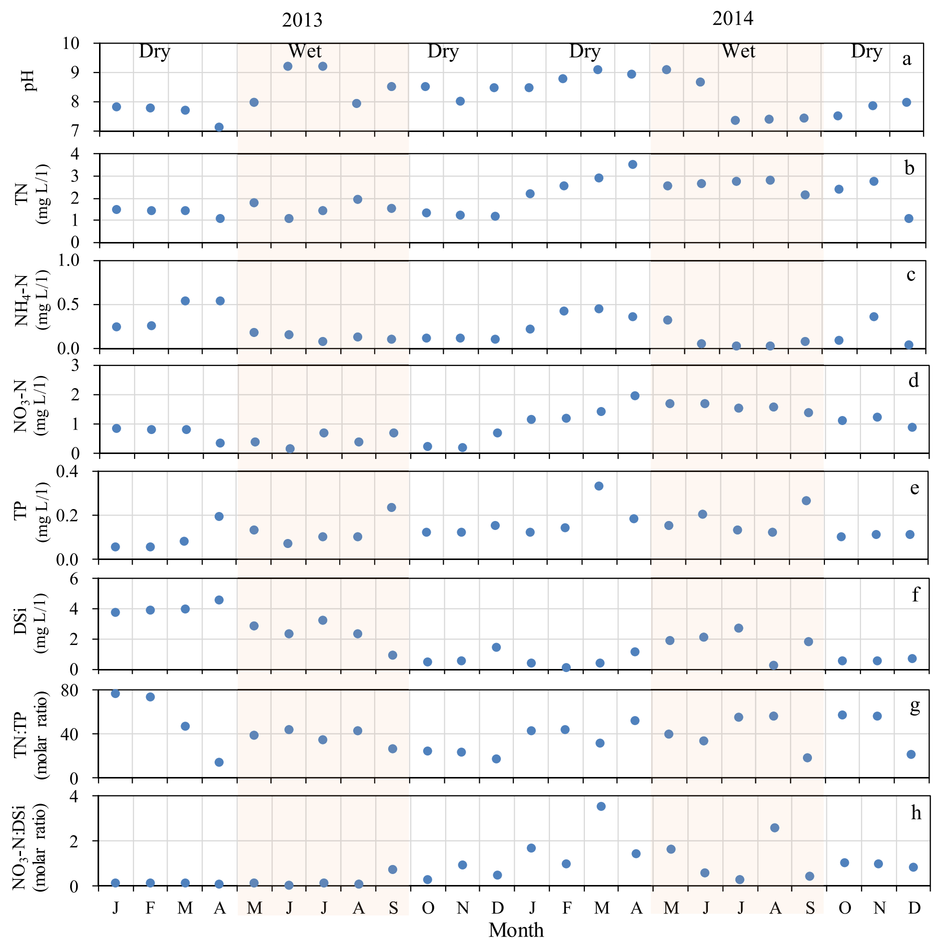

Fig. 5 – Seasonal variations of chemical variables in the Hanfeng Lake during 2013–2014. (a) pH, (b) TN, (c) NH_4-N, (d) NO_3-N, (e) TP, (f) DSi, (g) TN:TP, (h) NO_3-N:DSi.

Table. 2 – Forward stepwise regression analysis showing the potential predictors for Chl-*a* in different periods in the Hanfeng Lake.

Period	Regression model	*n*	R^2	P
Dry season	logChl-*a* = -1.99+3.93logDO-1.92logTN-0.32logDSi	14	0.964	0.000
Wet season	logChl-*a* = 0.034–0.533logV	10	0.502	0.022
Whole	logChl-*a* = 1.72–0.75logTN:TP	24	0.169	0.046

3. Discussion

Combination of water releasing and river flow recharge resulted in decrease in WD and increase in V and T in wet season. While substantial backflows from TGR played an opposite role in changes in WD, V and T in dry season (Table 1). These intensely hydrologic processes suppressed the seasonal variations in DO and Chl-*a*, and decoupled their interactions (Yang et al., 2017). DO only positively coupled with Chl-*a* in dry season which was experiencing high WD and low V and T. This was likely because water environmental condition with high water depth and low flow velocity was conducive to phytoplankton growth (i.e. increase in Chl-*a*) (Acuña et al., 2011; Li et al., 2015; Chen et al., 2018b), leading to increase in DO concentration (Wang et al., 2007). Chl-*a* was not correlated with T across all periods. This was contrasted with the finding of Fuentes and Petrucio (2015) who observed the positive correlation between water temperature and Chl-*a*. However, they also discussed that direct impacts of temperature rise were not a main factor causing the increase in phytoplankton biomass.

Water releasing and simultaneous river flow recharge overall contributed to decline in lake water volume but increase in inputs of chemical materials in wet season. In contrast, backflows favored phytoplankton activities in dry season, resulting in enhancement of pH values (Parinet et al., 2004). This might explain the positive relationships between pH and other chemical variables in different periods. TN was consistently changed with NO_3-N but not with NH_4-N, indicating the NO_3-N explained the most variance in TN. This was likely ascribed to the dominant nitrification (Liu and Luo, 2002), which

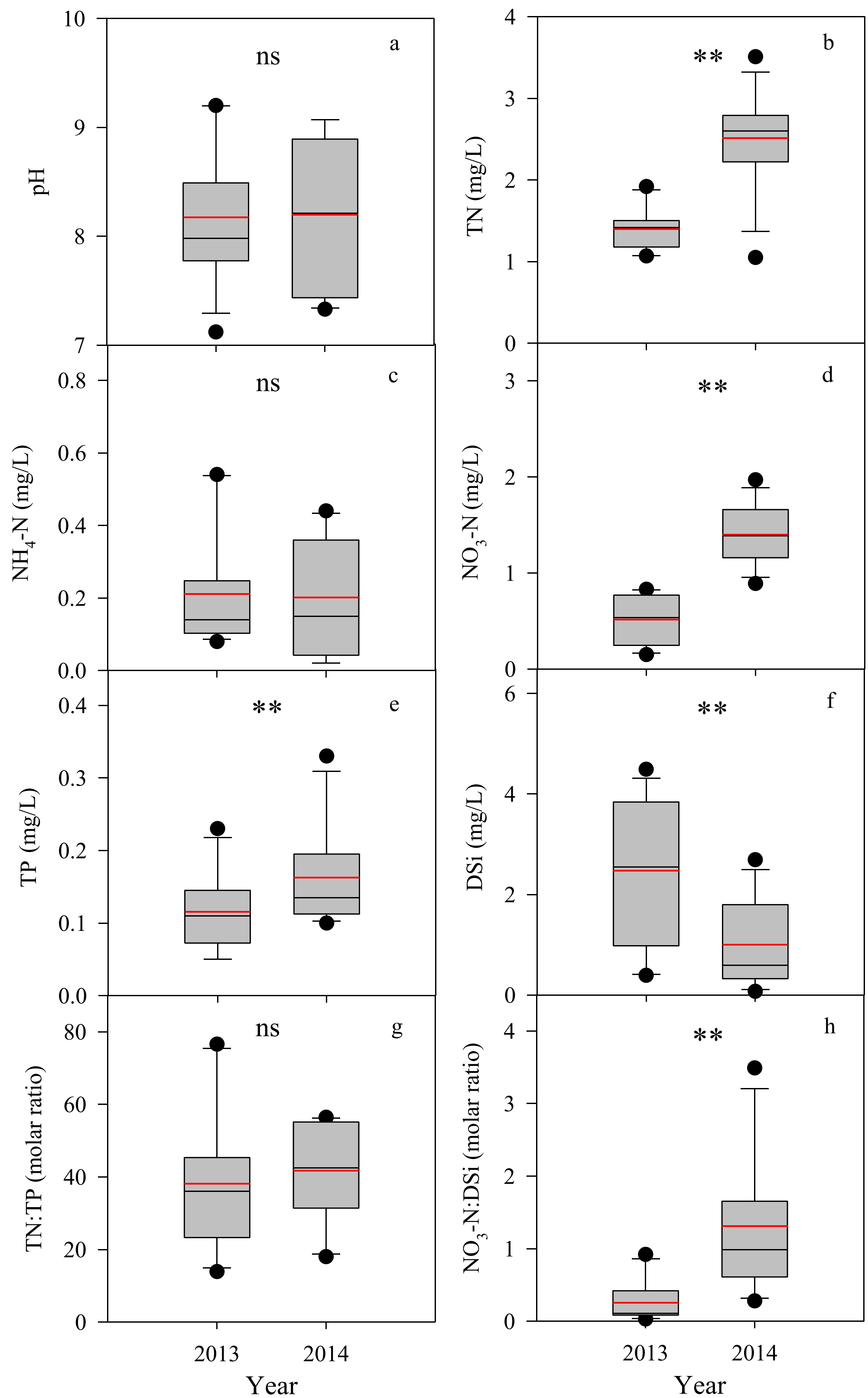

Fig. 6 – Boxplots showing differences on chemical variables between 2013 and 2014 in the Hanfeng Lake. (a) pH, (b) TN, (c) NH_4-N, (d) NO_3-N, (e) TP, (f) DSi, (g) TN:TP and (h) NO_3-N:DSi. Symbols of boxplot represented as follows: Mean data are red lines, Median data are black lines, 25th and 75th percentiles data are lower and upper edges, 10th and 90th percentiles are lower and upper bars and < 10th and > 90th percentiles data are lower and upper dots outside, respectively., the significance at $P<0.05$.**

was supported by the significantly positive relationship between NO_3-N and DO concentration. TP was not seasonal difference and correlated negatively with WD and positively with DO and pH in dry season. Dilution driven by backflows decreased TP concentration (Moatar et al., 2017), while photosynthesis of phytoplankton increased DO and pH, and the pH could exert decisive role in increasing P release from sediments (Jacoby et al., 1982; Søndergaard et al., 1999; Xie, 2006). Significantly positive relationship between DSi and V was likely caused by silicon input through the river flow recharge. TN:TP was always increased with the decrease in TP across all periods, which was similar to the previous finding (Wu et al., 2006). This was possibly due to different inputting sources for TN and TP (Downing and Mccauley, 1992) and the enhancement of algal growth (Smith, 1983). Xie et al. (2003) reported that cyanobacteria blooms enhanced P release from sediment due to photosynthetically-induced high pH, leading to increase in TP concentration and decrease in TN:TP in the water column. NO_3-N:DSi was almost explained equally by NO_3-N and DSi, implying the equivalent effects of NO_3-N and DSi on diatom activities (Wang et al., 2010; Hartmann et al., 2011).

Although Chl-*a* showed significant relationships with sparsely physicochemical variables in dry and the whole periods, the collinearity was found among those variables, which usually happened in water quality dataset and could cause the response deviation between interacted variables (Musolff et al., 2015). The FSRA confirmed these cases and complementally indicated that Chl-*a* was predictable by V in wet season. Chl-*a* increased with increasing of DO and decreasing of TN and DSi concentrations in dry season. This was probably because that the photosynthesis of phytoplankton could enhance DO release and simultaneously take up TN and DSi, and dilution driven by backflows also contributed to lower TN and DSi concentrations (Wang et al., 2007; Li et al., 2018). This result potentially suggested that TN and DSi were principally stemmed from the river flow discharge instead of backflows in Hanfeng Lake. Chl-*a* decreased with increase in V in wet season, supporting the findings of Mitrovic et al. (2011) who suggested that high flow velocity was beneficial to depress phytoplankton blooms. Chl-*a* was explained alone by TN:TP with 16.9% of the variance in the whole period, which was inconsistent with the finding of Yang et al. (2016) who found that pH solely, and jointly with euphotic depth, water level fluctuations and TP, explained 15.8% and 30.8% of the variance in cyanobacteria biomass respectively in subtropical reservoirs. This was likely attributed to that TN:TP could be comprehensively responsible for nutrient status affected by periodically hydrologic alteration in this study, demonstrating nitrogen and phosphorus concentrations regulated collectively the phytoplankton activities (Prairie et al., 1989; Bachmann et al., 2003; Huszar et al., 2006). Compiling a dataset from 33 subtropical shallow lakes in the middle and lower reaches of the Yangtze River, Wu et al. (2006) reported that phytoplankton biomass was correlated negatively with TN:TP when TP was lower than 0.035 mg/L but positively with TN:TP when TP was higher than 0.1 mg/L, irrespective of season variability. This was a little different from our result that negative relationship between Chl-*a* and TN:TP was not affected by any TP thresholds. These differences might result from the periodically hydrologic alterations occurred in this study. Our result further suggested that reduction in N concentration and increase in P could therefore increase Chl-*a* concentration, which was in good agreement with the previous finding (Filstrup and Downing, 2017). Here, it is worthy noted that although different physical and chemical variables were found to be correlated with Chl-*a* in terms of season variability, historically, the water residence time, a key variable for reservoir limnology, has been strongly adopted to elucidate the physical, chemical and biotic variabilities (e.g. Chl-*a*) in aquatic ecosystems (Straškraba et al., 1993; Soares et al., 2008; Catalán et al., 2016). This parameter was not used in this study due to limited data on outflowing water discharge, but its potential is strongly attractive to be assessed in Hanfeng Lake and/or other backwater zones of TGR in the future.

Moreover, our results found that TN (average 1.96 mg/L) and TP (average 0.14 mg/L) concentrations both exceeded the eutrophic level (TN: 0.2 mg/L, TP: 0.02 m/L) of freshwater ecosystems (Li et al., 2015). However, Chl-*a* concentration averaged 4.93 μg/L was much lower than the 10 μg/L level for eutrophication, potentially suggesting the rare occurrences of algal blooms in Hanfeng Lake. TN:TP with an average of 40:1 was much higher than the Redfield ratio 16:1 (Redfield, 1958). This probably resulted in changes in species composition of phytoplankton communities and further impairment of lake food-web performance (Guildford and Hecky, 2000; Elser et al., 2009; Wang et al., 2020). Likewise, NO_3-N:DSi averaged 0.8:1 was lower than the classical 1:1, indicating probably increased proportion of diatoms in phytoplankton assemblages (Turner et al., 2003). Although the Chl-*a* concentration was low relative to eutrophic level, the imbalance of stoichiometric ratio of nutrients (e.g. N, P and Si) emphasized the potential shifts in phytoplankton community composition, which in turn influenced the changes in physicochemical indicators linked with water quality. A long-term dataset is needed to explore the relationships between phytoplankton performance and nutrient stoichiometry and their associations with common physicochemical variables under the conditions of periodically hydrologic alterations.

4. Conclusions

Shifts in physicochemical properties and Chl-*a* were interpreted monthly in the dam-induced Hanfeng Lake from January 2013 to December 2014. WD and NH_4-N concentration were significantly higher in dry season than in wet season, while the opposite trend was true for V and T. Chl-*a* and others were not seasonal differences during the study period. T, TN, NO_3-N, TP, DSi and NO_3-N:DSi presented inter-annual variability. Higher TN:TP and lower NO_3-N:DSi relative to balanced stoichiometric ratio suggested possibly shifts in species composition of phytoplankton communities and increased proportion of diatom in the lake. Chl-*a* was better explained by combination of DO, TN and DSi in dry season, and was predictable by V in wet season and by TN:TP in the whole study period, respectively. The results revealed that periodically hydrologic alterations considerably decoupled the relationships between physicochemical parameters and Chl-*a* in Hanfeng lake. This study also highlights the effects of damming on changes in water environment under the heightened human activities and climate change, and provides valuable information for sustainable management of water resources and water quality for dam-induced urban lake system and other aquatic systems under analogous conditions worldwide.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jes.2020.06.014.

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