FACTORS INFLUENCING CHLOROPHYLL *A* CONCENTRATION IN THE YANGTZE-CONNECTED LAKES

Bao-Zhu Pan[1,2], Hai-Jun Wang[1], Xiao-Min Liang[1], Hong-Zhu Wang[1]

[1]State Key Laboratory of Freshwater Ecology and Biotechnology, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan 430072, P.R. China

[2]Graduate School of the Chinese Academy of Sciences, Beijing 100039, P.R. China

ABSTRACT

To determine the environmental factors influencing phytoplankton chlorophyll *a* (Chl *a*), field investigations were conducted in three river-connected lakes (Dongting Lake, Poyang Lake and Shijiu Lake) of the Yangtze floodplain in 2004. Results showed that the average Chl *a* concentration in these lakes ranged from 2.98 to 3.65 mg m^{-3}. The major factors influencing Chl *a* in lentic and lotic regions were total phosphorus (TP) and water velocity (U), respectively. Multiple relationships including total nitrogen ($\log_{10}$TN) and water depth ($\log_{10}$Z) were established. Further analyses found that the absolute Chl *a* and slope of $\log_{10}$Chl $a=f$ ($\log_{10}$TP) in the river-connected lakes were obviously lower than those in the river-isolated lakes. This suggests the river-lake connectivity can significantly modify relationship between TP and chlorophyll a concentration.

KEYWORDS: chlorophyll *a*, water velocity, total phosphorus, river-connected lakes.

INTRODUCTION

Chlorophyll *a* (Chl *a*) is widely used as a measure of phytoplankton biomass. It has been associated with many factors in the former researches. Studies on lentic system, e.g. in temperate and subtropical lakes and reservoirs, confirmed the strong dependence of Chl *a* concentration on total phosphorus (TP) [1-4]. The nutrient-Chl *a* relationship was generally a non-linear function with large unexplained variations, suggesting that other factors also limit algal growth, e.g. physical ones (water depth, water temperature, light), and biotic ones (predation, competition) [5, 6]. With regard to lotic system, e.g. in rivers and their associated waters, Chl *a* concentration was usually found to be influenced more strongly by water-flow than by nutrients [7-9]. Additionally, Chl *a* concentration may vary with catchment area, water depth, or other physical factors [10, 11].

As one of the largest floodplains in the world, the Yangtze River floodplain is characterized by numerous shallow lakes, which were freely connected with the Yangtze River historically. To prevent villages and cultivated lands along the lakeshore from being flooded, embankments and sluice gates were constructed during the 1950s-70s, and thereby isolated most lakes from the river. At present, only three lakes (Dongting Lake, Poyang Lake and Shijiu Lake) have direct connections with the Yangtze mainstem. As a mosaic of lentic and lotic patches, these river-connected lakes are a kind of special waterbodies, being intermediate between lentic and lotic systems. Therefore, it is of scientific significance to analyze factors influencing Chl *a* concentration in these special waters. How-ever, previous studies of phytoplankton chlorophyll in Yangtze basin were mainly concentrated on isolated lakes [4, 12-15]. Little work has been done on the connected lakes [16, 17].

In view of the special hydrologic regime, the regulation on Chl *a* concentration of the Yangtze-connected lakes should receive attention. To determine environmental factors influencing Chl *a* concentration, we conducted systematic investigations in three Yangtze-connected lakes in 2004.

STUDY AREA AND METHODS

Dongting Lake, Poyang Lake and Shijiu Lake are river-connected lakes, situated in the mid-lower Yangtze basin, or, in other words, located in the monsoon region of East Asia subtropical zone. The locations and limnological parameters of study lakes are given in Fig. 1 and Table 1, respectively.

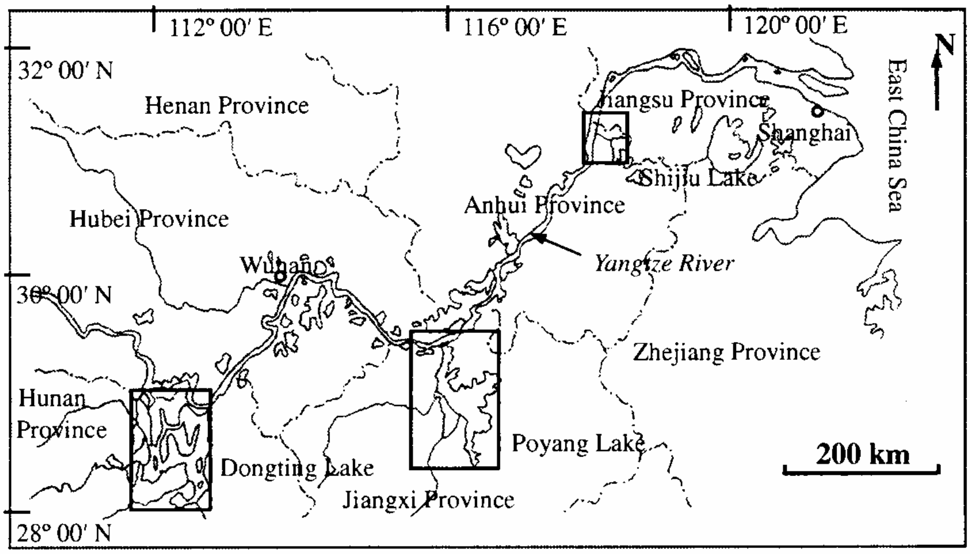

FIGURE 1 - Location of study lakes. Numbers of sampling sites in Dongting Lake, Poyang Lake and Shijiu Lake are 30, 22 and 7, respectively.

TABLE 1 - Limnological parameters of the Yangtze-connected lakes.

Lake	Dongting Lake	Poyang Lake	Shijiu Lake
Area (km^2)	2432 (33.0 m ASL)	2933 (21.7 m ASL)	210.4 (9.3 m ASL)
Maximum (Mean) depth (m)	23.5 (6.4)	29.2 (5.1)	5.3 (4.1)
Annual mean water level fluctuation (m)	5.90	5.86	3.10
Annual precipitation (mm)	1200-1450	1340-1780	569-1685
Annual evaporation (mm)	1174-1420	800-1200	900-1100
Annual water input (10^8 m^3)	3065.7	1501.2	78.4
Retention time (d)	18.2	10.0	41.0
Annual mean air temperature (℃)	16.8	16.6	16.0
Annual mean water temperature (℃)	16.7	16.5	--
pH	8.1	7.3	7.8
Annual mean water sediment concentration (g m^{-3})	127	66	--
Dominant algae	Cryptophyta, Bacillariophyta	Bacillariophyta	Chlorophyta, Euglenophyta

ASL = above sea level. Data were from related materials [16-18].

Phytoplankton chlorophyll *a* (Chl *a*) was investigated in May-July (high water level) and September-December (low water level) 2004. Water depth (Z) and transparency (Z_{SD}) were measured with a sounding lead and a Secchi Disc, respectively. Water velocity (U) was measured with a propeller-type current meter (Model LS 1206B). Water samples were taken from surface and bottom at each site, mixed, and brought back to laboratory for analyses. Suspended solids (SS) was analyzed according to APHA [19], and total nitrogen (TN) by the alkaline potassium persulfate digestion-UV spectrophotometric method. TP was analyzed by the ammonium molybdate method. Chl *a* concentration was measured after acetone extractions by reading absorbance at 665 nm and 750 nm using a spectrophotometer (Unico UV-2000, Shanghai, China). All the above methods were described in detail by Huang [20]. Macrophytes were sampled with a scythe, 2-4 times at each site, then cleaned, superfluous water removed, and weighed for wet weight (B_{Mac}).

STATISTICA 6.0 was used for analyses of Pearson correlation, Unequal N HSD test after one-way ANOVA, multiple regression analysis. To reduce heterogeneity of variances, U data were transformed to $U^{0.5}$ and other variables were log_{10}-transformed. Macrophyte biomass (B_{Mac}) was transformed to $log_{10}(B_{Mac}+1)$.

RESULTS

Chlorophyll *a* concentrations and environmental parameters

Data from 59 sampling sites in 10 regions were examined. It seemed that phytoplankton chlorophyll *a* (Chl *a*) was closely related to certain environmental factors, especially to water velocity (U) at many sites. Hence, all sites were grouped into lotic sites and lentic sites based on the velocity, and then tested by means of one-way ANOVA. It demonstrated that Chl *a*, U and several velocity-related parameters were significantly different between two groups of sites. Overall results are given in Table 2.

TABLE 2 - Phytoplankton chlorophyll *a* concentrations and environmental parameters (mean ± SE) of study sites (with comparison of parameters between two groups of sites in the last two rows).

	Regions	Chl *a*	T	SS	Z	Z_{SD}	U	TN	TP	B_{Mac}
Dongting Lake	West Dongting	2.79±0.81	22.3±0.8	0.054±0.018	3.2±0.4	86±10	0.42±0.02	1157±116	154±15	386±249
	South Dongting	1.96±0.38	22.9±0.9	0.032±0.001	2.2±0.2	42±9	0.39±0.03	1089±161	152±19	0±0
	Dunhu	4.90±1.90	26.6±0.4	0.037±0.001	2.4±0.2	168±9	0.00±0.00	927±191	59±19	563±299
	East Dongting	3.20±0.68	22.5±1.6	0.032±0.005	4.7±0.7	41±4	0.07±0.01	1977±267	148±16	0±0
	Junshanhouhu	9.67±2.25	23.5±2.0	0.024±0.010	3.8±0.7	87±21	0.01±0.00	1425±146	82±25	0±0
	Entire Lake	3.03±0.43	21.4±0.7	0.030±0.004	3.7±0.3	75±6	0.23±0.02	1400±100	132±8	179±88
Poyang Lake	Banghu	1.51±0.24	26.2±0.9	0.031±0.019	2.4±0.2	184±25	0.02±0.00	491±93	35±12	1014±201
	Dahuchi	0.85±0.17	27.0±0.9	0.017±0.011	1.9±0.1	144±8	0.00±0.00	563±200	36±10	727±252
	Changhuchi	2.40±0.63	27.9±1.3	0.073±0.025	2.1±0.0	114±38	0.00±0.00	1038±466	40±13	440±216
	Dachahu	2.57±0.38	25.6±0.8	0.020±0.007	3.0±0.1	118±15	0.02±0.01	1257±116	15±2	299±107
	Entire Lake	2.11±0.43	25.5±0.6	0.030±0.008	3.7±0.3	139±12	0.02±0.00	953±107	25±4	545±96
Shijiu Lake		5.91±0.98	27.9±0.6	0.036±0.017	2.5±0.2	104±8	0.00±0.00	647±105	89±8	346±117
All lotic sites		2.07±0.17[a]	22.1±0.7[a]	0.029±0.005[a]	4.1±0.3[a]	83±8[a]	0.21±0.02[a]	1467±132[a]	126±11[a]	174±52[a]
All lentic sites		4.99±0.78[b]	25.6±0.8[a]	0.034±0.007[b]	2.8±0.2[b]	110±9[a]	0.00±0.00[b]	1030±107[b]	63±8[b]	354±75[a]

Chl *a*, phytoplankton chlorophyll *a* (mg m^{-3}); SS, suspended solids (kg m^{-3}); Z, water depth (m); Z_{SD}, transparency (cm); U, water velocity (m s^{-1}); TP, total phosphorus concentration of water (mg m^{-3}); TN, total nitrogen concentration of water (mg m^{-3}); B_{Mac}, macrophyte biomass (g m^{-2}). Means with different superscripts are significantly different (p<0.05).

According to the Chl *a* standard suggested 1996 by Nürnberg [21] for fixed boundary classification of lake system, 15.6% of lentic sites were in eutrophic-hypertrophic state, and all lotic sites in oligotrophic-mesotrophic state (Fig. 2).

Since river-connected lakes have lotic and lentic regions, the following analyses referring to the influencing factors of Chl *a* will be given according to respective regions.

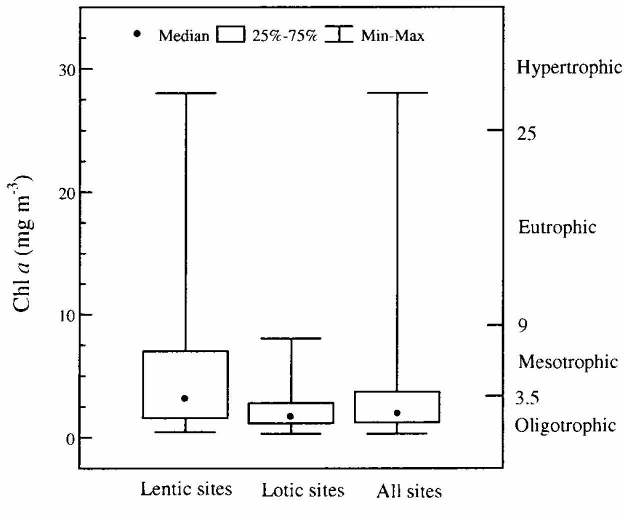

FIGURE 2 - Box lines of chlorophyll *a* concentration. Trophic states determination according to the fixed boundary classification system [21].

Factors influencing chlorophyll *a* in lentic regions

In lentic regions, correlations between phytoplankton chlorophyll *a* (Chl *a*) and environmental parameters (Table 3) indicated that TP was the major factor influencing Chl *a*. The regression of $\log_{10}$TP-$\log_{10}$Chl *a* is given in Fig. 3.

The relations of residuals from $\log_{10}$TP-$\log_{10}$Chl *a* regression to water depth (Z) and TN were significant (Table 4). Adding Z and TN as driving variables, R^2 of multiple regression model could increase obviously. The equation was as follows:

$\log_{10}Chl a=-1.42+0.51\log_{10}TP+0.29\log_{10}TN+0.71\log_{10}Z$ (R^2=0.36 n=43 p=0.001).

Factors influencing chlorophyll *a* in lotic regions

Pearson correlation analyses (Table 3) showed that water velocity (U) and TN were most important in determining Chl *a* in lotic regions. Further regression analyses revealed that a higher amount of variance in $\log_{10}$Chl *a* was accounted for by $U^{0.5}$ (Fig. 4a, parabola, r^2=0.34), compared to $\log_{10}$TN (Fig. 4b, linear, r^2=0.16). Therefore, the major factor influencing Chl *a* should be U.

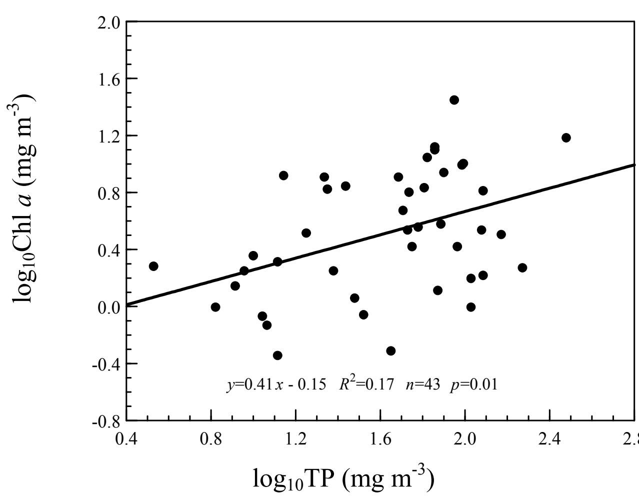

FIGURE 3 - Regression between total phosphorus ($\log_{10}$TP) and chlorophyll *a* concentration ($\log_{10}$Chl *a*) in lentic sites of the Yangtze-connected lakes.

TABLE 3 - Pearson correlation coefficients (*r*) between chlorophyll *a* concentration and environmental factors in lentic sites (upper triangle) and lotic sites (lower triangle) (0.001≤*p*<0.05 denoted as "*", *p*<0.001 denoted as "").**

	$\log_{10}$Chl *a*	$\log_{10}$T	$\log_{10}$SS	$\log_{10}$Z	$\log_{10}Z_{SD}$	$U^{0.5}$	$\log_{10}$TP	$\log_{10}$TN	$\log_{10}$(TN:TP)	$\log_{10}(B_{Mac}+1)$
$\log_{10}$Chl *a*		-0.09	-0.08	0.19	-0.31*	--	0.42*	0.29	-0.09	-0.30*
$\log_{10}$T	-0.22		-0.27	0.29	0.61**	--	-0.31*	-0.45**	-0.05	0.34*
$\log_{10}$SS	0.29	-0.37		-0.39*	-0.43*	--	0.39*	-0.26	-0.55*	-0.04
$\log_{10}$Z	-0.13	0.08	0.08		0.30*	--	-0.38*	0.18	0.40*	-0.24
$\log_{10}Z_{SD}$	0.09	0.27	-0.07	-0.04		--	-0.53**	-0.54**	0.01	0.31
$U^{0.5}$	-0.39*	-0.17	0.27	0.10	-0.33*		--	--	--	--
$\log_{10}$TP	-0.01	-0.35*	0.63**	0.02	-0.35*	0.63**		0.09	-0.71**	-0.18
$\log_{10}$TN	0.39*	-0.57**	0.34	-0.03	-0.28*	-0.04	0.18		0.65**	-0.35*
$\log_{10}$(TN:TP)	0.22	0.08	-0.50*	-0.05	0.30*	-0.62**	-0.90**	0.34*		-0.04
$\log_{10}(B_{Mac}+1)$	-0.10	0.22	-0.42*	-0.18	0.44**	-0.46**	-0.50**	-0.36*	0.37*	

TABLE 4 - Pearson correlations between residuals of $\log_{10}$Chl *a*=*f* ($\log_{10}$TP) and environmental factors in lentic sites (0.001≤ *p*<0.05 denoted as "*").

	$\log_{10}$T	$\log_{10}$SS	$\log_{10}$Z	$\log_{10}Z_{SD}$
r	-0.03	-0.24	0.37*	-0.19
p	0.85	0.24	0.02	0.22
	$U^{0.5}$	$\log_{10}$TN	$\log_{10}$(TN:TP)	$\log_{10}(B_{Mac}+1)$
r	--	0.35*	0.23	-0.31
p	--	0.02	0.15	0.05

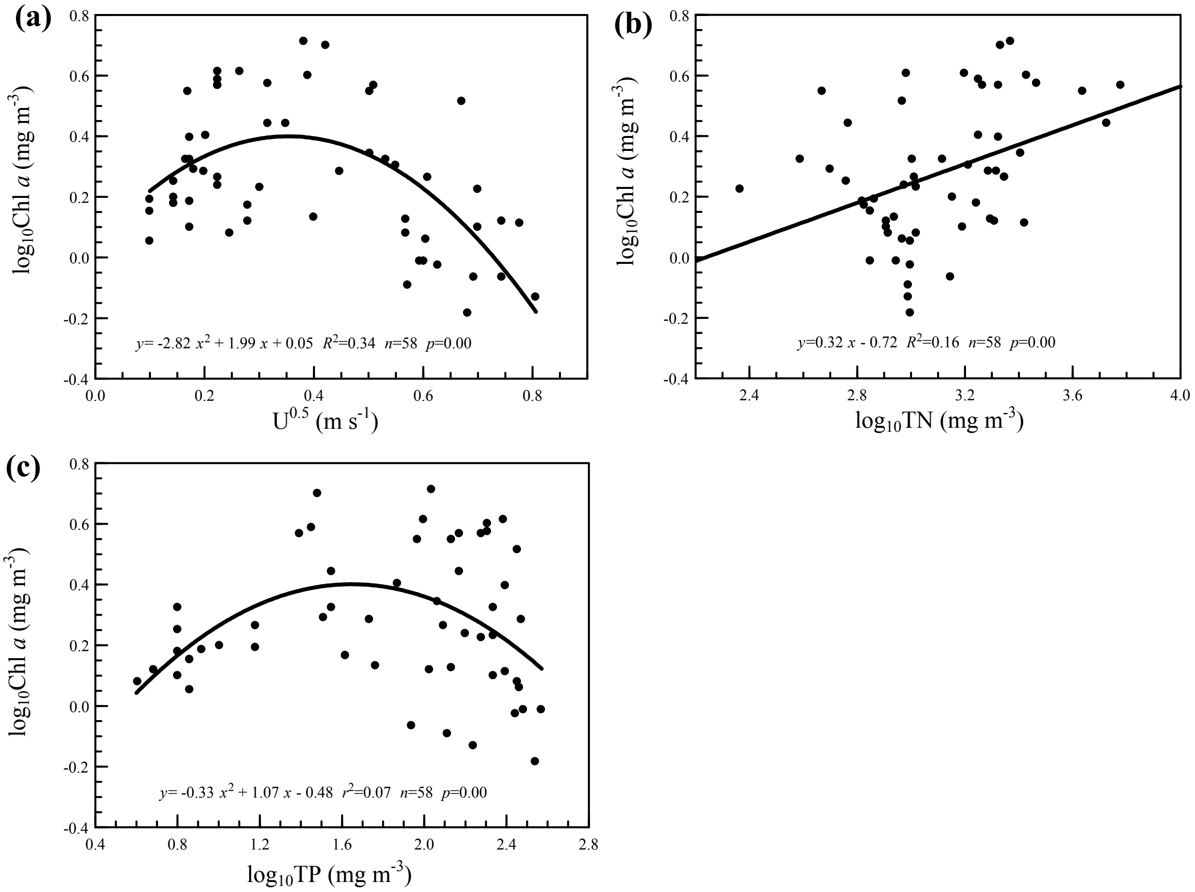

FIGURE 4 - Regressions between environmental factors and chlorophyll *a* concentration ($\log_{10}$Chl *a*) in lotic sites of the Yangtze-connected lakes. *x*-axes are (a) water velocity ($U^{0.5}$), (b) total nitrogen ($\log_{10}$TN), (c) total phosphorus ($\log_{10}$TP).

TABLE 5 - Pearson correlations between residuals of $\log_{10}$Chl $a=f(U^{0.5})$ and environmental factors in lotic sites ($0.001 \leq p<0.05$ denoted as "*").

	$\log_{10}$T	$\log_{10}$SS	$\log_{10}$Z	$\log_{10}Z_{SD}$
r	-0.13	0.22	0.33*	0.07
p	0.39	0.27	0.02	0.59
	$\log_{10}$TN	$\log_{10}$TP	$\log_{10}$(TN:TP)	$\log_{10}(B_{Mac}+1)$
r	0.35*	0.11	0.08	-0.14
p	0.01	0.44	0.59	0.32

The relations of residuals from $U^{0.5}$-$\log_{10}$Chl *a* regression to water depth (Z) and TN were significant (Table 5). Similar to the above results, R^2 of multiple regression model could obviously increased by adding Z and TN as driving variables. The equation was $\log_{10}$Chl a = -0.51-2.16$U^{0.5}$+ 1.37$\log_{10}$TN+0.23$\log_{10}$Z (R^2=0.47 n=58 p<0.001).

DISCUSSION

The average phytoplankton Chl*a* of Yangtze-connected lakes ranged from 2.98 to 3.65 mg m^{-3}, higher than the range of 0.52-2.88 mg m^{-3} in the mainstream and tributaries of the Yangtze River [22, 23], but lower than the range of 3.17-26.5 mg m^{-3} in Yangtze-isolated lakes [4, 24]. The differences are considered to be mainly attributed to water residence times, which are much shorter in lotic waters than in lentic environment. River-connected lakes have lentic and lotic regions, therefore, they are regarded as partly lotic, so that their residence times and chlorophyll *a* concentrate are intermediate.

A positive relationship between water velocity (U) and TP in lotic regions was found in our work (Fig. 5). Previous researches also reported that higher flow was closely linked to greater input of external nutrient sources [10, 11]. However, higher nutrient concentrations do not necessarily translate into a larger phytoplankton biomass under lotic conditions. As shown in Fig. 4a, $U^{0.5}$-$\log_{10}$Chl *a* relationship in lotic regions is parabolic. When U is below 0.12 m/s, Chl *a* tends to increase with velocity. In this situation, phytoplankton biomass is thought to be determined mainly by nutrient concentrations. When U exceeds 0.12 m/s, Chl *a* tends to decline, suggesting that U inhibition has prevailed over nutrients effects on growth of algae. High U may cause high concentrations of SS, resulting in light limitation on algal growth. (cf. Table 3). Sand pellets carried by high water flow may spoil cell walls of phytoplankton [25]. High water flow, i.e. short residence time, increases phytoplankton losses by wash-out effects [11].

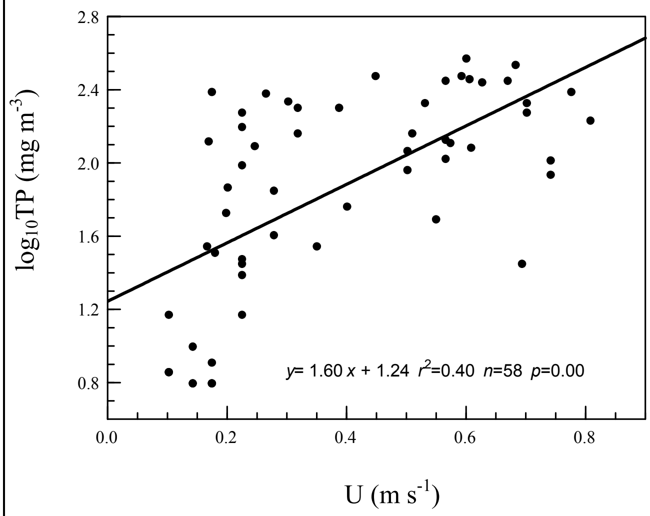

FIGURE 5-Regression between water velocity ($U^{0.5}$) and total phosphorus ($\log_{10}$TP) in lotic sites of the Yangtze-connected lakes.

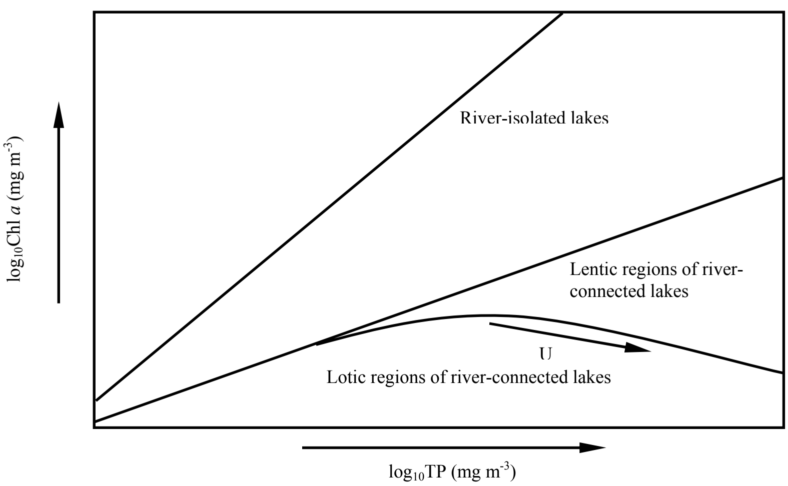

FIGURE 6 - Comparison of phosphorus-chlorophyll *a* regression lines from Yangtze-connected and Yangtze-isolated lakes.

The relationships of $\log_{10}$TP-$\log_{10}$Chl *a* in two types of Yangtze lakes are compared (Fig. 6). Both regressions in river-isolated lakes and lentic regions of river-connected lakes are linear. The slope of the former is 1.04 [4], within the range of the slopes (0.87-1.21) of foreign lakes [3, 26, 27]. The slope of lentic regions of river-connected lakes is 0.41, about 1/3 of that of river-isolated lakes. This disparity is mainly attributed to the different residence times. The regression derived from lotic regions in river-connected lakes is curvilinear, with the slope negative. This character is considered to be a result of synthetic effects of TP and U.

CONCLUSIONS

According to phytoplankton Chl *a*-level in fixed boundary classification system, some regions in three Yangtze-connected lakes were found to be in eutrophic state. Statistical analyses indicate that Chl *a* values in lentic and lotic regions were mainly influenced by TP and water velocity U, respectively. A brief comparison of TP-Chl *a* relationships among the Yangtze-isolated lakes, lentic and lotic regions of the Yangtze-connected lakes is given as well. The obviously lower Chl *a* concentration and slope of $\log_{10}$Chl $a = f(\log_{10}\text{TP})$ in river-connected lakes demonstrated that the river-lake connectivity can significantly modify relationship between TP and Chl *a* concentrations.

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CORRESPONDING AUTHOR

Hong-Zhu Wang
State Key Laboratory of
Freshwater Ecology and Biotechnology
Institute of Hydrobiology
Chinese Academy of Sciences
430072 Wuhan, Hubei Province
P.R. CHINA

Phone/Fax: +86 27 68780719
E-mail: wanghz@ihb.ac.cn