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Eutrophication and algal blooms in channel type reservoirs: A novel enclosure experiment by changing light intensity

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Abstract

To explore eutrophication and algal bloom mechanisms in channel type reservoirs, a novel enclosure experiment was conducted by changing light intensity (LI) in the Daning River of the Three Gorges Reservoir (TGR). Square enclosures (side 5.0 m) were covered on the surface with shading materials of different thickness, and with their bases open to the river. Changes and characteristics of the main eutrophication factors under the same water quality and hydrodynamic conditions but different LI were evaluated. All experimental water samples were neutral and alkalescent, with high nitrogen and phosphate concentrations, low potassium permanganate index, stable water quality, and different LI. At the same water depth, LI decreased with increasing shade material, while dissolved oxygen and water temperature were both stable. The growth peak of phytoplankton was with light of 345–4390 lux underwater or 558–7450 lux above the water surface, and water temperature of 25.6–26.5˚C. Algae were observed in all water samples, accounting for 6 phylum and 57 species, with algal density changing frequently. The results showed that significantly strong or weak light was unfavorable for phytoplankton growth and the function together with suitable temperature and LI and ample sunshine encouraged algal blooms under the same water quality and hydrodynamic conditions. Correlation analysis indicated that algae reduced gradually lengthwise along water depth in the same enclosure while pH became high. The power exponent relationship between chlorophyll a (Chl-*a*) and LI was found by curve fitting, that is Chl-$a = K(\mathrm{LI})^n$.

Key words: eutrophication; algal bloom; enclosure experiment; channel type reservoirs; Three Gorges Reservoir

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Introduction

The occurrence of toxic cyanobacterial blooms in eutrophic lakes, reservoirs and recreational waters has become a worldwide problem (Carmichael, 2001; Song et al., 2007). With large dams having been built in more than 150 countries, with most of the 45,000 dams found in developing countries, the contamination of eutrophication and algal blooms in these reservoirs has received increasing attention (Zeng et al., 2006; Zheng et al., 2008; Cao et al., 2008a).

The Three Gorges Reservoir (TGR) in China is the world's largest dam, measuring 2309 m long and 185 m high and forming an area of 1084 km^2 by 2009 (Wu et al., 2003; Zeng et al., 2006). The construction of the Three Gorges Project can be divided into preparation and first stage (1993–1997), second stage (1998–2003) and third stage (2004–2009). The water level at dam completion fluctuates between 175 m (rainy season) and 145 m (dry season) while the current level of TGR is approximately 170 m. The dam's turbines generate tremendous electric power and the reservoir is designed to help control flooding. In addition, the TGR will allow large ships to enter China's interior and will provide irrigation and drinking water. However, large scale dams are seldom constructed without associated environmental problems (Snow et al., 2000; Vörösmarty et al., 2003). Damming alters the characteristics of a water body, replacing riverine conditions with those of a lake and affecting not only the hydrology but also the physical, chemical, and biological nature of the system. These changes include increases in residence time and stratification, decreases in particles, and sometimes an increase in primary production (Friedl and Wüest, 2002; Cheng and Li, 2001). Not only can large dams affect characteristics of individual rivers, they may also have a cumulative effect on the phytoplankton composition and biogeochemical cycling in coastal seas (Humborg et al., 1997). There have been more and more outbreaks of algal blooms in the anabranch of the TGR since construction was completed (Zhang, 2005; Cao et al., 2009). Numerous

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studies on nutrients releasing and population dynamics of riverine phytoplankton and composition of phytoplankton have been conducted all over the country (Zhang, 2005; Zeng et al., 2006, 2007; Cao et al., 2009). However, little information is available in the literature about the relationship of light intensity (LI) and algal blooms. Since phytogeographic studies have shown close physiological relationships between LI and the distribution of individual phytoplankton species (Watson et al., 2004; Baek et al., 2008; Mortillaro et al., 2009), research clarifying the problem LI and outbreaks of eutrophication and algal bloom is required.

Since the 1960s, researchers have investigated and developed technologies and methods for controlling algal blooms (Schindler, 2006; Carpenter, 2008; Lewis and Wurtsbaugh, 2008; Conley et al., 2009), involving physical and mechanical methods such as manual clearing alga, ball clay flocculating, and changing light intensities (Han and Kim, 2001; Pan et al., 2003; Shen et al., 2004), chemical methods such as biocide clearing alga (Cao et al., 2008b), and biotechnologies such as growth of other safe algae, microorganism, flocculating, bio-controlling reagents, plant repression, and fish feeding (Codd, 2000; Xie, 2003). As for the TGR, changing LI is the only practical method of controlling alga and clearing algal blooms as it should have no impact on hydrodynamic or water quality conditions.

An alternative way of studying the mechanism of eutrophication and algal blooms is the use of experimental mesocosms or enclosures which control experimental conditions. Most such studies have been carried out in laboratory conditions or in land-based mesocosms (Sullivan et al., 1991; Rhew et al., 1999). Enclosure experiments in natural intact water bodies have usually been conducted in lakes (Cottingham et al., 1997; Suomela et al., 2005), but seldom in riverine conditions (Smetacek et al., 1982). The comparison of enclosures with different LI offers a way to not only study the effect of LI on algal blooms, but also to evaluate the changes and characteristics of eutrophication factors. Until recently, however, few such studies have been conducted.

In the present study, a novel enclosure experiment with changing LI was performed to survey the fate of LI and algal growth and the relationship of eutrophication factors in the anabranch of TGR. The aim was to clarify algal bloom outbreak mechanisms in channel type reservoirs such as TGR. In addition, this study traced the fate of supporting potential technologies and methods to control algal blooms.

1 Materials and methods

1.1 Study site

According to backwater changing, hydrographic conditions and outbreak characteristics of algal bloom in Daning River of TGR, the study site was located in Dong Pingbar of Daning River where algal blooms have broken out frequently over the past years (31°08′39.1″N, 109°54′24.8″E, Fig. 1) (Zhang, 2005; Cao, 2009; Cao et al., 2009). The wide experimental river in Dong Pingbar is located between Bawu Gorge outlet and the upper reaches of Baishui River, and between Long-men Gorge and Bawu Gorge in the “Little Three Gorges” scenic spot of Daning River. Dong Pingbar became a slow-flow lake with Pi-Bazhou Island in the middle after TGR reached

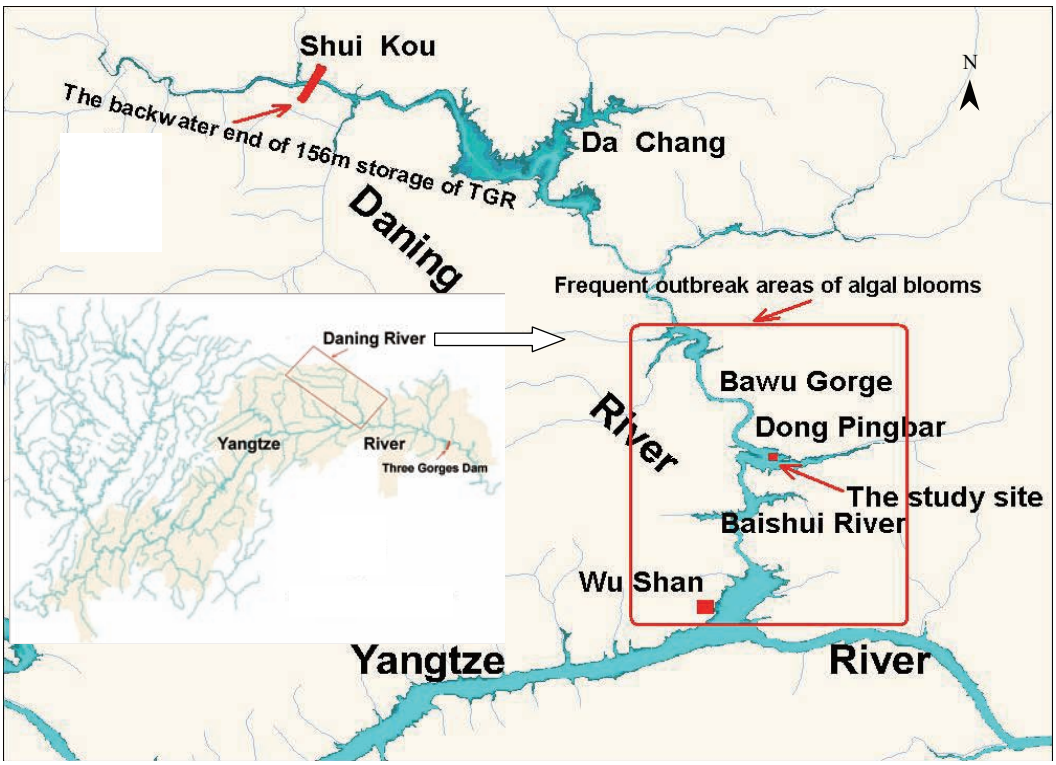

Fig. 1 Map of large on-the-spot enclosure experiment in the Three Gorges Reservoir (TGR).

156 m storage. Many farmlands and towns were inundated, which caused the severe slow release of pollution from the submerged soil (Zhong, 2004; Cao et al., 2009). In addition, water pollution became increasingly serious with the growing scale of net-cage fish culture in the area (Cao et al., 2009; Cao, 2009). Such factors have made Dong Pingbar highly susceptible to frequent algal bloom outbreaks, algal blooms have occurred each year between March and June since the TGR began to store water.

1.2 Experimental design

All enclosures covered with different shading materials were placed in the study area. Relationships among eutrophication factors such as chlorophyll a (Chl-*a*), light intensity (LI), and water temperature (WT) at different water depth were investigated under the same water quality and hydrodynamic conditions but with different LI.

To protect the algae in the experimental water from the surrounds, the experimental enclosures were separated from each other designated by firm and durable waterproof materials which sat 2.0 m above water and 3.0 m underwater. The enclosure surface were covered by shading materials of different thickness, and the enclosure bases were open to allow for water exchange with the surroundings, and therefore maintain the same water quality, water temperature, and water velocity. There were five experimental groups in this study, specifically, 0# control-experimental enclosure without any shade materials on surface (0# group), 1# experimental enclosure with one piece of shade material (1# group), 2# experimental enclosure with two pieces of shade materials (2# group), 3# experimental enclosure with three pieces of shade materials (3# group), and the Dong Pingbar control-experiment group, whose sampling was collected from the surrounding water of enclosures (Dong Pingbar group).

1.3 Enclosure building and using

The enclosures were placed in an east to west direction in the study river. They were square, made of firm durable transparent polyethylene, and included a floating body, side wall, top covering material and fixed installation (Fig. 2).

The floating body was a square structure with floating framework and floaters, which was used to keep the top of enclosure out of the water and allowed the whole setup to be suspended. (1) The floating framework was a 10.0 m×10.0 m square framework divided equally into four square sub-enclosures with 5.0 m sides, and was formed by many steel tubes linked with each other. The four corners of each sub-enclosure stood vertically a 5.0 m-length steel tube respectively (2.0 m above water and 3.0 m underwater), those of whole setup accounted for 9. Each joint was linked into an integral structure by strong fasteners. (2) Floaters were made of several empty petrol tanks with high sealing performance. All tanks were the diameter of 80 cm, height of 120 cm, and load-bearing of 603 kg. The number of floaters was determined by the actual total weight of the whole enclosure, sample-staff and experimental instruments together.

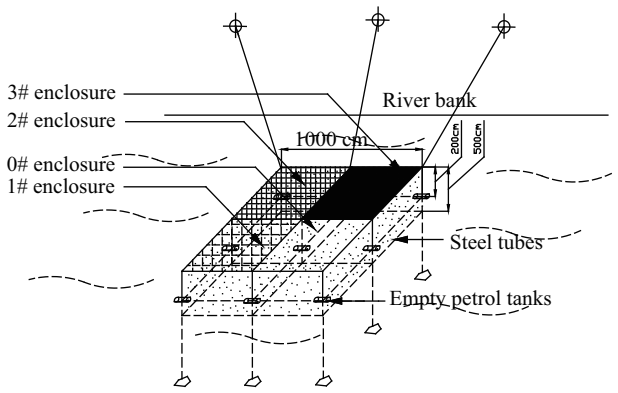

Fig. 2 Sketch of enclosure experimental setup.

The side wall was made up of waterproof materials surrounding the enclosure wall to prevent phytoplankton and irrelevant substances from entering the enclosures. The bases of all enclosures were open to maintain the same water quality conditions with the surrounding water. The side walls, which were 1.5 m above water and 3 m underwater, were fixed with the nine steels tubes mentioned above. The sub-enclosures were also isolated from each other by side walls. An outlet of the side wall and a narrow wooden footbridge above the poles in each sub-enclosure were used for convenient sampling.

Top covering material was made from shade fabrics available in the market. No shade materials were placed on the surface of 0# enclosure, one piece of shade material was used in 1# enclosure, two pieces in 2# enclosure, and 3 pieces in 3# enclosure. All top covering materials were fixed with the nine steels tubes and linked with the side wall. There was a 0.5 m high gap between the top covering materials and the side wall to maintain the same WT and hydrodynamic conditions between the enclosures and the surrounding water.

The fixed installation was several big rocks and ropes. The rocks were sunk onto the river bed, and fixed to the setup by ropes. The setup was then fixed on the river bank by three ropes.

The whole experimental area was encircled by nylon fishing net 1.0 m from the side wall of the enclosure. It was indispensable to fix the traffic warning board after enclosure building completed.

1.4 Sampling and analysis

The experiment lasted for 19 days (14 May–2 June 2008). The first sampling was conducted at 2–5 p.m., the peak time of algal growth (Jin and Tu, 1990; Jin, 1995), on 22 May and then at intervals of three or four days. Samples were taken at 0.5, 1.0, 1.5, 2.0, 3.0 and 5.0 m depth. Four subsamples from different quarters of the enclosure were pooled in a single sample. Water samples were taken from the enclosures and the surrounding river. Each water sample was divided into two individual samples, one of which was used for analyzing water quality and one for phytoplankton. After collection, the samples for water quality measurement were filtered immediately through

pre-cleaned, 0.45 μm pore-size, acetate cellulose filters, presoaked in diluted hydrochloric acid (pH < 2) overnight and then rinsed with Milli-Q water (SEPA, 2002). The parameters were analyzed both in filtered and unfiltered samples. Samples for phytoplankton were selected by a vertical sampler, and fixed with Lugol's iodine solution (SEPA, 2002; Jin and Tu, 1990).

The samples were analyzed for water temperature (WT), water depth, pH, suspender substance (SS), total N (TN), total dissolved N (TDN), dissolved inorganic N (DIN), total P (TP), total dissolved P (TDP), potassium permanganate index (COD_{Mn}), dissolved oxygen (DO), chlorophyll a (Chl-*a*) and phytoplankton identification and enumeration. Other important parameters were also measured such as air temperature (AT), water level, altitude, longitude and latitude, Secchi Disc (SD), and light intensity (LI, above and under of water).

The AT, WT, pH and DO were measured with a portable Multiline LDO101 HQ40d DO analyzer with two selectable LDO IntelliCAL probes (HACH, USA). Altitude and sampling site were oriented with portable GPS locator. Above-water and underwater LI was analyzed with a ZDS-10-W-2D luxmeter.

Samples for TP were digested with $K_2S_2O_8$ in acidic conditions and measured spectrophotometrically as ammonium molybdate blue complex (SEPA, 2002). The TN was measured by digesting the sample with $K_2S_2O_8$ to nitrate, which was further reduced to nitrite and measured in an FIA-ionanalysator (SEPA, 2002). Both NO_3^- and NO_2^- were analyzed with pbenoldisulfonic acid spectrophotometry and N-(1-naphthyl)-quadrol spectrophotometry methods, respectively, and NH_4^+ was measured spectrophotometrically with indophenols blue. The (NO_3^- + NO_2^- + NH_4^+) was analyzed as DIN. The TN and TP concentrations of filtering samples were defined as TDN and TDP, respectively, according to previous publications (SEPA, 2002; Cao et al., 2009) and GB3838.

Fixed phytoplankton were identified and enumerated by an OLYMPUS-CX31 light microscope (Olympus, Japan), according to commonly used monographs on phytoplankton (Jin and Tu, 1990; Eker et al., 1999; SEPA, 2002; Zhao, 2005). Correlation and regression were both analyzed with SPSS16.0 using bivariate correlation and two-tailed tests. Significance was determined at an alpha level of 0.05 and 0.01 ($p \leqslant 0.05$ and $p \leqslant 0.01$) (Chen and Huang, 2002; Liu et al., 2008; Chen and Xu, 2006).

2 Results

2.1 Character of conventional physicochemical parameters in enclosure experiment

In the present study, conventional physicochemical parameters were systematically investigated in the enclosure experiment. All waters in the enclosure experiment were neutral and alkalescent, and pH varied between 7.45 and 8.64 (mean value was 8.37). The pH increased gradually from the $0^{\#}$ to $3^{\#}$ enclosure. Nitrogen and phosphate concentrations in all water samples were so high that outclassed the value of the threshold of algae spindling (TN is 0.2 mg/L and TP is 0.02 mg/L) (Zheng et al., 2008; Cao et al., 2009). The water quality conditions (e.g. TN, DIN, TP, SS) in each enclosure were nearly the same as the bottoms were open to natural water. The TN and TP of the $2^{\#}$ and $3^{\#}$ groups were slightly higher than in the $0^{\#}$ and $1^{\#}$ groups, but the DIN and TDP concentrations were almost equal due to the bioaccumulation to nitrogen and phosphate from more algal growth in $2^{\#}$ and $3^{\#}$. The potassium permanganate index was very low, with little difference observed in the different enclosures (Table 1).

2.2 Distribution of major eutrophication factors in enclosure experiment

Total sampling was conducted at 2–5 a.m. from 20 May to 2 June 2008, when LI was high and algae grew actively. Figure 3 shows the distributions of major eutrophication factors (Chl-*a*, LI, DO and WT) of the enclosure experiment lengthwise along water depth.

2.2.1 Light intensity

The LI varied between 29 and 22,600 lux, and lessened gradually from 0.5 m above water to 5.0 m underwater in each group. At the same depth of water, LI decreased with increasing shade materials (from $0^{\#}$ or Dong Pingbar group to $3^{\#}$ group). The LI of the $2^{\#}$ and $3^{\#}$ groups changed slightly. The mean value of LI at the surface of the $3^{\#}$ enclosure was equivalent to the LI 5.0 m underwater in the $0^{\#}$ enclosure or Dong Pingbar group. Both the $0^{\#}$ group and Dong Pingbar group had the same LI values at the same time (some slight differences only came from different sampling time). The LI of all waters at 5.0 m underwater was very low and tended towards stability (Fig. 3).

Table 1 Conventional physicochemical parameters in enclosure experiment

Group		pH	TN (mg/L)	DIN (mg/L)	TP (mg/L)	TDP (mg/L)	SS (mg/L)	COD_{Mn} (mg/L)
0#	Range	8.21–8.35	1.51–2.06	1.47–2.03	0.041–0.065	0.031–0.050	2.30–8.30	2.18–2.74
	Mean	8.33	1.80	1.68	0.053	0.040	4.79	2.34
1#	Range	7.45–8.55	1.55–2.08	1.51–1.83	0.036–0.070	0.031–0.050	2.00–10.00	2.19–2.78
	Mean	8.34	1.80	1.70	0.054	0.041	5.05	2.46
2#	Range	8.25–8.54	1.55–2.10	1.48–1.86	0.055–0.075	0.036–0.050	2.00–12.70	2.29–2.72
	Mean	8.39	1.85	1.65	0.062	0.043	5.23	2.51
3#	Range	8.25–8.64	1.38–2.14	1.26–2.11	0.055–0.070	0.036–0.050	2.00–10.70	2.16–2.94
	Mean	8.41	1.84	1.68	0.061	0.042	5.36	2.42
Dong Pingbar	Range	8.25–8.49	1.51–2.20	1.34–2.20	0.036–0.075	0.026–0.045	1.70–8.30	2.16–2.62
	Mean	8.36	1.87	1.71	0.059	0.037	4.69	2.36

TN: total N; DIN: dissolved inorganic N; TP: total P; TDP: total dissolved P; SS: suspender substance; COD_{Mn}: potassium permanganate index

2.2.2 Dissolved oxygen and water temperature

During this experiment, DO varied between 6.69 and 12.49 mg/L in all waters (mean value 9.51 mg/L), and WT varied between 22.9 and 28.3°C (mean value is 24.9°C) (Fig. 3). They both lessened gradually from 0.5 to 5.0 m underwater, and only slight differences existed among the enclosures and between the enclosures and the surrounding water.

2.2.3 Chlorophyll *a*

The Chl-*a* concentrations in the enclosures and the surrounding water varied between 0.58 and 17.48 mg/m^3. The values of 26 May 2008 in the 2$^{\#}$ enclosure and Dong Pingbar and of 2 June 2008 in the 2$^{\#}$and 3$^{\#}$ enclosures were 17.48, 17.47, 16.67, and 15.45 mg/m^3, respectively (Table 2) (> 11 mg/m^3, the value of a threshold of eutrophication in lakes and reservoirs (Jin and Tu, 1990; Jin, 1995)) and were all higher than the others. High values were obtained on sunny days with strong light (Fig. 3b, d) and weak values were observed on cloudy or rainy days (Fig. 3a, c), which indicated the Chl-*a* concentrations were related to weather and sunshine duration. Lengthwise along water depth, the concentrations reduced gradually. The peak Chl-*a* values of all groups were found at 0.5 m underwater, and the minimum values were at 5.0 m underwater. Slight differences existed among the enclosures and between the enclosures and the surrounding water. Low LI was not conducive to algal growth, and thus the suitable range was about 0.5 m underwater.

2.3 Investigation of phytoplankton in enclosure experiment

In the phytoplankton surveys for all enclosures and the surrounding water, 57 species of algae from 6 phyla were observed. Their densities changed frequently, among which Bacillariophyta was dominant followed by Chlorophyta and Cyanophyta. Algae decreased gradually lengthwise along water depth, and were active from 0.5 to 1.5 m underwater. The peak values of algal species and densities appeared at a depth of 0.5 m, but decreased significantly from 3.0 to 5.0 m underwater. The trends of algal densities were the same as Chl-*a* concentrations, whereby high values were observed on 26 May 2008 of 2$^{\#}$ group and Dong Pingbar and 2 June 2008 of 2$^{\#}$ and 3$^{\#}$ groups (Table 2).

2.4 Correlation analysis of major eutrophication factors in all enclosures

There were significant positive correlations between Chl-*a* and LI and WT in the 0$^{\#}$ enclosure ($r > 0.5$, $\alpha = 0.05$) and significant negative correlations between Chl-*a* and WD ($r = –0.502$, $\alpha = 0.05$) (Table 3), which showed that algae grew rapidly with increasing LI and WT and reduced gradually lengthwise along water depth in the 0$^{\#}$ enclosure. Water depth also exhibited significant negative correlations with LI, DO, and WT ($|r| > 0.6$, $\alpha = 0.01$). Significant positive correlations were also observed among LI, DO, and WT ($r > 0.75$, $\alpha = 0.01$) and they had all significant negative correlations with WD, which indicated that the four parameters of the 0$^{\#}$ enclosure were close each other. Algae rapid growth and increasing WT may result in increasing DO in water.

Significant positive correlations were observed between Chl-*a* and TP and TDP ($r_{\text{Chl-}a\text{-TP}} = 0.501$, $\alpha = 0.05$; $r_{\text{Chl-}a\text{-TDP}} = 0.631$, $\alpha = 0.01$) in Dong Pingbar group (Table 3), which indicated algae growth was close with phosphorus (especially dissolved phosphorus). This was in accord with the conclusion that phosphorus is the restrictive factor of nutrient salts in the TGR (Zhong, 2004; Zheng et al., 2008; Cao et al., 2008a).

Both LI and DO had significant negative correlations with WD ($|r| > 0.6$, $\alpha = 0.01$) in Dong Pingbar Group.

Table 2 Distributions of Chl-*a*, algal density, and dominant species in enclosure experiment during peak of phytoplankton growth

Date	Group	Chl-*a* (mg/m^3)	Algal density(cells/L)	Dominant species
2008–05–26	2#	17.48	421803	Schroederia of Chlorophyta
	Dong Pingbar	17.47	317881	Selenastrum of Chlorophyta
2008–06–02	2#	16.67	360672	Coelastrum and Pandorina of Chlorophyta
	3#	15.45	434029	Pandorina of Chlorophyta

Table 3 Correlation analysis of eutrophication factors in Dong Pingbar group and 0$^{\#}$ enclosure[a]

	Chl-*a*	WD	TN	TP	TDP	DIN	LI	DO	WT	pH
Chl*a*	1	–0.502*	0.039	–0.433	–0.412	–0.157	0.508*	0.336	0.609*	0.052
WD	(–0.474)[b]	1	0.005	0.439	0.251	–0.060	–0.658**	–0.854**	–0.644**	-0.485
TN	(–0.075)	(0.005)	1	–0.352	–0.266	0.771**	0.478	0.172	0.383	–0.237
TP	(0.501*)	(–0.132)	(–0.509*)	1	0.902**	–0.390	–0.591*	–0.590*	–0.853**	–0.582*
TDP	(0.631**)	(–0.209)	(–0.442)	(0.768**)	1	–0.343	–0.546*	–0.409	–0.751**	–0.533*
DIN	(–0.100)	(0.131)	(0.849**)	(–0.521*)	(–0.313)	1	0.606*	0.417	0.468	0.011
LI	(0.449)	(–0.636**)	(–0.510*)	(0.256)	(0.417)	(–0.424)	1	0.764**	0.850**	0.333
DO	(0.223)	(–0.817**)	(–0.013)	(–0.225)	(0.139)	(–0.013)	(0.652**)	1	0.768**	0.559*
WT	(0.391)	(–0.581*)	(–0.110)	(–0.305)	(0.150)	(–0.073)	(0.657**)	(0.830**)	1	0.523*
pH	(0.192)	(–0.438)	(0.249)	(0.177)	(0.067)	(–0.088)	(–0.056)	(0.255)	(–0.043)	1

* Significant at the 0.05 (2-tailed test), ** significant at the 0.01 (2-tailed test).
[a]: Data were analyzed by SPSS16.0, $N = 16$.
[b]: Data using parentheses were the correlate results of Dong Pingbar control-experimental group.
Chl-*a*: chlorophyll *a*, WD: water depth, LI: light intensity, DO: dissolved oxygen, WT: water temperature.

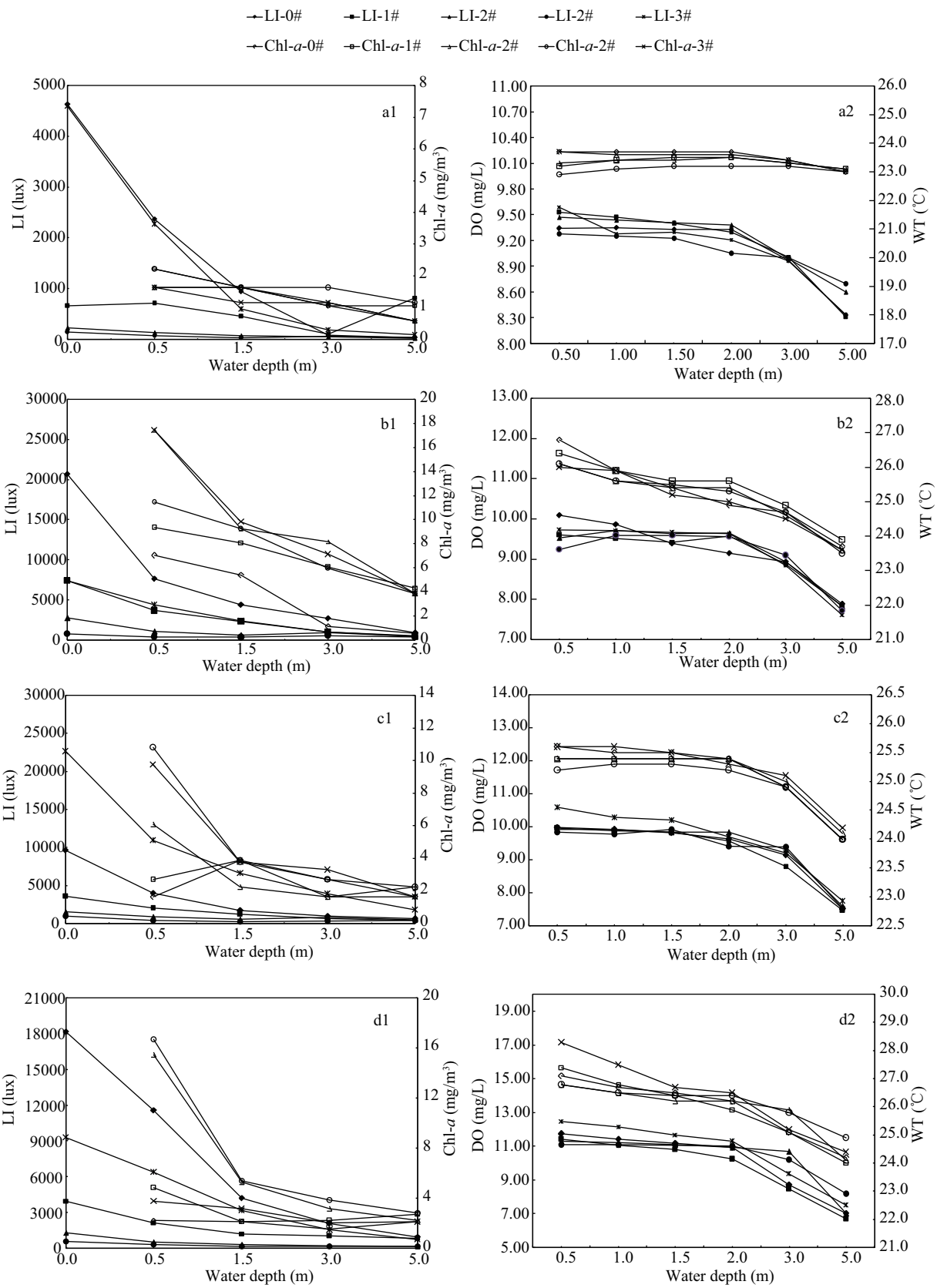

Fig. 3 Results of enclosure experiment. The differences of LI between $0^{\#}$ group and Dong Pingbar group came from different sampling times. (a1, a2) experimental results of 22 May 2008; (b1, b2) experimental results of 26 May 2008; (c1, c2) experimental results of 29 May 2008; (d1, d2) experimental results of 2 June 2008. LI: light intensity; Chl-*a*: chlorophyll a; WT: water temperature; DO: dissolved oxygen.

This was different from the $0^{\#}$ enclosure in that Chl-*a* exhibited no strong correlation with LI, DO and WT and the correlation between WT and WD declined slightly. These differences may relate to differences in sampling time, as it was not possible to collect samples from the $0^{\#}$ enclosure and Dong Pingbar water at the same time.

Sampling in the 0# enclosure generally occurred one hour earlier than in Dong Pingbar, and therefore may have influenced the lower LI and WT observed in Dong Pingbar.

Chl-*a* had significant positive correlations with LI and WT in 1#, 2# and 3# enclosures ($r > 0.5$, $\alpha = 0.05$), and significant negative correlations with WD in 2# and 3# enclosures respectively ($|r| > 0.5$, $\alpha = 0.05$) (Table 4). The change of LI was different for all experimental groups. The LI of 0# enclosure and Dong Pingbar group had both significant positive correlations with WD ($|r| > 0.6$, $\alpha = 0.01$), while the correlation gradually weakened in 1# enclosure ($r = –0.597$, $\alpha = 0.05$), and was almost non-existent in 2# and 3# enclosures. The correlation between WT and WD decreased slowly with increasing shade material, and the correlation coefficients (r) reduced gradually from $r = –0.644$ ($\alpha = 0.01$) for 0# enclosure and $r = –0.581$ ($\alpha = 0.05$) for Dong Pingbar to $r = –0.565$ ($\alpha = 0.05$) for 1# enclosure, $r = –0.536$ ($\alpha = 0.05$) for 2# enclosure, and no correlation in 3# enclosure. These results showed that LI and WT for all groups changed because of shading function. Significant positive correlations were found between DO and WD in all groups ($|r| > 0.7$, $\alpha = 0.01$), which suggested that LI changes had no influence over DO. The pH of the 2# and 3# enclosures had both significant negative correlations with WD ($|r| > 0.5$, $\alpha = 0.05$ and 0.01 respectively), which was likely due to algae overgrowing. The pH of water can influence both algal growth and algal death (Cao, 2009; Cao et al., 2009). Because the enclosure waters were separated from the surrounding water surfaces, pH increased gradually with algae decreasing lengthwise along water depth.

2.5 Regression analysis of major eutrophication factors in enclosure experiment

2.5.1 Linear regression

The physicochemical data of all experimental groups were analyzed with SPSS16.0. The regression equation contained all parameters. For the stepwise regression equation, however, significant variables were contained step by step during the course of regression according to the setting standards while insignificant variables were excluded, and the regression was not completed until there were no more additions or exclusions (Chen and Huang, 2002; Liu et al., 2008; Chen and Xu, 2006). In this study, close factors with algal growth were selected such as Chl-*a*, WD, LI, TN, TP, TDP, DIN, DO, WT and pH.

Regression equations for all groups showed significant relationships ($R^2 > 0.46$ and $p < 0.01$) (Table 5). The equations of Dong Pingbar control-experimental group and 0# enclosure experimental group contained 8 parameters (DO, WT, WD, DIN, TP, pH, TDP and TN, Table 5) and 3 parameters (WT, DIN and pH, Table 5) respectively, which indicated that their Chl-*a* concentrations were both governed by a combination of multi-parameters. However, only one parameter (LI) in 1# enclosure equation, one parameter (WT) in 2# enclosure equation, and two parameters (WT and TP) in 3# enclosure equation were observed. This showed that LI had significant influence on the Chl-*a* of 1# enclosure, WT significantly influenced Chl-*a* of 2# enclosure, and WT and TP had significant influence on Chl-*a* in 3# enclosure. The parameter number selected by the regression equations of 1#, 2#, and 3# enclosures was all much less than them of Dong Pingbar control-experimental group equation, while their determination coefficients were not significantly reduced ($R^2 > 0.46$, $p < 0.01$), which showed that the regression significance were not greatly decreased with reduced parameters, and the equations were easier to use in practice.

2.5.2 Curve fitting

Curve fitting is a data processing method based on experimental data. Combined with other methods such as theoretical analysis and scatter diagrams, curves that best fit the data are selected (Chen and Huang, 2002; Liu et al., 2008; Chen and Xu, 2006). In this study,

Table 4 Correlation analysis of eutrophication factors in 1#, 2#, and 3# enclosures

	Chl-*a*	WD	TN	TP	TDP	DIN	LI	DO	WT	pH
Chl-*a*	1	–0.364	0.031	–0.183	0.065	0.078	0.810**	0.228	0.579*	0.115
WD	(–0.525*)[a] [–0.601*][b]	1	–0.077	0.104	–0.074	–0.091	–0.597*	–0.863**	–0.565*	–0.124
TN	(0.391) [0.481]	(–0.279) [–0.123]	1	–0.724**	–0.776**	0.718**	0.037	0.254	0.399	–0.045
TP	(0.298) [0.499*]	(–0.186) [-0.393]	(–0.405) [0.194]	1	0.780**	–0.387	–0.348	–0.170	–0.652**	0.119
TDP	(–0.075) [0.433]	(–0.063) [–0.115]	(–0.003) [–0.123]	(0.415) [0.742**]	1	-0.337	0.004	–0.081	–0.494	0.186
DIN	(0.500*) [0.285]	(–0.103) [0.100]	(0.639**) [–0.838**]	(–0.339) [0.005]	(–0.113) [–0.206]	1	0.008	0.282	0.241	0.254
LI	(0.666**) [0.546*]	(–0.357) [–0.051]	(–0.118) [0.060]	(0.510*) [0.475]	(–0.105) [0.712]	(–0.011) [–0.032]	1	0.475	0.749**	0.138
DO	(0.409) [0.538*]	(–0.767**) [–0.737**]	(0.203) [0.275]	(–0.079) [0.063]	(–0.057) [-0.084]	(0.023) [0.065]	(0.159) [–0.093]	1	0.665**	0.088
WT	(0.697**) [0.736**]	(–0.536*) [–0.436]	(0.042) [0.248]	(0.044) [0.174]	(–0.403) [0.276]	(0.201) [0.084]	(0.576*) [0.433]	(0.709**) [0.679**]	1	–0.012
pH	(0.059) [0.292]	(–0.595*) [–0.741**]	(0.574*) [-0.016]	(–0.011) [0.402]	(0.306) [0.156]	(0.053) [–0.296]	(–0.206) [-0.011]	(0.389) [0.384]	(–0.170) [–0.043]	1

* Significance at the 0.05 (2-tailed test), ** Significant at the 0.01 (2-tailed test).

Data using parentheses were the correlation results of 2# enclosure; data using square brackets were the correlation results of 3# enclosure, the rest were 1# enclosure.

Table 5 Results of regression analysis of enclosure experiment

Group	Regression equation	R^2	F	p	Factor*
Dong Pingbar	Chl-a = –223.588 – 1.882(WD) – 1.142(TN)+157.227(TP) +201.089(TDP)+9.647(DIN) – 5.066(DO) +4.156(WT)+17.420(pH)	0.931	9.022	0.007	DO, WT, WD, DIN, TP, pH, TDP and TN
0#	Chl-a = 69.201+1.788(WT) – 10.231(DIN) – 11.299(pH)	0.866	25.864	0.000	WT, DIN and pH
1#	Chl-a = 0.946 + 0.002(LI)	0.656	26.747	0.000	LI
2#	Chl-a = –67.951 + 2.955(WT)	0.468	13.245	0.003	WT
3#	Chl-a = – 71.927 + 2.335(WT) + 319.408(TP)	0.684	14.041	0.001	WT and TP

* Sorting by the influence on dependent variable (Chl-a) from big to weak.

Table 6 Frequently-used essential linear models

Model	Regression equation	Linear equation after variable being transformed
Quadratic	$y=\beta_0+\beta_1 x+\beta_2 x^2$	$y=\beta_0+\beta_1 x+\beta_2 x_1 \quad (x_1=x^2)$
Compound	$y=\beta_0+\beta_1^x$	$\ln(y)=\ln(\beta_0)+\ln(\beta_1)x$
Growth	$y=e^{(\beta_0+\beta_1^x)}$	$\ln(y)=\beta_0+\beta_1 x$
Logarithmic	$y=\beta_0+\beta_1\ln(x)$	$y=\beta_0+\beta_1 x_1 \quad (x_1=\ln(x))$
Cubic	$y=\beta_0+\beta_1 x+\beta_2 x^2+\beta_3 x^3$	$y=\beta_0+\beta_1 x+\beta_2 x_1+\beta_3 x_2 \ (x_1=x^2,\ x_2=x^3)$
S	$y=e^{\beta_0+\beta_1/x}$	$\ln(y)=\beta_0+\beta_1 x_1 \quad (x_1=1/x)$
Exponential	$y=\beta_0(e^{\beta_1 x})$	$\ln(y)=\ln(\beta_0)+\beta_1 x$
Inverse	$y=\beta_0+\beta_1/x$	$y=\beta_0+\beta_1 x_1 \quad (x_1=1/x)$
Power	$y=\beta_0(x^{\beta_1})$	$\ln(y)=\ln(\beta_0)+\beta_1 x_1 \quad (x_1=\ln(x))$
Logistic	$y=\frac{1}{\frac{1}{\mu}+\beta_0\beta_1^x}$	$\ln(\frac{1}{y}-\frac{1}{\mu})=\ln(\beta_0+\ln(\beta_1)x)$

Table 7 Results of curve fitting of enclosure experiment

Group	Equation	R^2	F	p	Significance
Dong Pingbar	Chl-a = 0.094(LI)$^{0.472}$	0.468	12.337	0.003	Significant
0#	Chl-a = 0.220(LI)$^{0.289}$	0.424	10.311	0.006	Significant
1#	Chl-a = 0.060(LI)$^{0.569}$	0.542	16.578	0.001	Significant
2#	Chl-a = 0.066(LI)$^{0.685}$	0.599	20.932	0.000	Significant
3#	Chl-a = 0.141(LI)$^{0.635}$	0.535	16.134	0.001	Significant

Table 8 Parameter values of enclosure experiment during peak of phytoplankton growth

	Group	Chl-a (mg/m^3)	LI (lux)*		WT (°C)	DO (mg/L)
2008-05-26	2#	17.48	1130	2800	25.6	9.72
	Dong Pingbar	17.47	4390	7450	25.9	9.72
2008-06-02	2#	16.67	345	558	26.5	11.10
	3#	15.45	528	1307	26.5	11.23

The first group data of LI were the values 0.5 m underwater, and the second group data were the values at the surface above water.

the curves between LI and Chl-a in all enclosures were fitted by SPSS16.0 according to frequently-used essential linear models (Table 6), and curve fitting were selected by high coefficients of determination (R^2) and considering theoretical knowledge of eutrophication (Table 7).

The curve fitting results indicated that the power exponent relationship between Chl$a$ and light intensity was found in all enclosures, that is Chl-a = K(LI)^n and the constants of K and n were determined by shade materials. The test results of $R^2 > 0.42$ and $p < 0.01$ showed that each equation was significant.

3 Discussion

3.1 Eigenvalues of eutrophication factors during the phytoplankton peak

Phytoplankton growth is affected by many factors, including nutrient salts, WT, pH, DO, and LI (Rhew, 1999; Baek et al., 2008; Mortillaro et al., 2009). In the present study, water quality and hydrodynamic conditions were not influencing factors as the bases of all enclosures were open to the river. We examined the relationship between LI and phytoplankton growth, and distributions

of eutrophication factors at different water depth during the phytoplankton peak. The Chl-*a* concentrations on 29 May 2008 in 3# enclosure and 2 June 2008 in 2#and 3# enclosures were both higher than that in the Dong Pingbar control-experimental group and 0# enclosure on 29 May 2008 and 2 June 2008. However, the opposite result was found in relation to LI, which indicated that high levels of LI were not advantageous to phytoplankton growth. The Chl-*a* concentrations of 26 May 2008 in 2# enclosure and the Dong Pingbar group were both of a high level (7.48 and 17.47 mg/m^3, respectively) and showed no significant differences; however, their LI values were significantly different. Although the LI were very high on 22 May 2008 in 0# enclosure and the Dong Pingbar group (values at a depth of 0.5 m underwater exceeded 2000 lux), the Chl-*a* concentrations were low and there was no dramatic phytoplankton growth, which likely related to the low temperature (< 24°C) and minimal sunshine days. These results indicated that the function together with suitable temperature and LI and ample light application time resulted in algal blooms under the same water quality and hydrodynamic conditions. Table 8 displays the values of the main factors in the growth peak of phytoplankton (Chl-*a* > 11 mg/m^3).

The results shown in Table 8 demonstrate that the LI varied between 345 and 4390 lux at 0.5 m underwater and between 558 lux and 7450 lux on the surface above water, and the range of WT was from 25.6 to 26.5°C when Chl-*a* was at a high level. The conclusions from the present study show significant differences from the small scale laboratory eutrophication experiment on illumination intensity simulated by pumping raw water from Yangtze River in TGR, which indicated that the LI ranged from 5200 to 7300 lux surface above water was good for algal growth under still water laboratory conditions (Zhong, 2004). The main reason for the observed differences is that the laboratory experiment mainly studied the relationship between illumination intensity and algal growth of raw water under otherwise equal conditions, while the emphasis of the present study was based on natural and complex field conditions. Such conditions had many obvious advantages for phytoplankton, such as natural and diverse phytoplankton ecosystems, unique terrains and landforms, suitable climate and abundant nutrients. Together with hydrodynamic conditions typically associated with reservoirs (long water residence times, low water velocity, and varied water levels), as opposed to laboratory simulating, these factors combine with one other and complex causative factors were responsible for the increased LI observed in this study (McGregor and Fabbro, 2000; Burford and O'Donohue, 2006; Leigh et al., 2010). In addition, different LI measuring instruments may have some influence on the different results (Zhong, 2004).

3.2 Relation between Chl-*a* and other eutrophication factors

Many studies have revealed correlativity among eutrophication factors. In the 1970s, the OECD founded correlativity between the mean concentrations of TP and Chl-*a* and SD in lakes and between SD and Chl-*a* through extensive and thorough monitoring and analysis of 200 lakes worldwide (Jin, 1995; Prairie et al., 1989). Many later studies further expounded the quantitative relationship among eutrophication factors in the world's lakes (Zeng et al., 2007; Zhang, 2005). To investigate the causes of algal bloom and eutrophication, we conducted a series of studies including distributions of nitrogen and phosphorus in the major input rivers (Zheng et al., 2008; Cao et al., 2008a), characteristics of algal blooms (Cao, 2009), and contrast research on winter and spring algal blooms (Cao et al., 2009) in the anabranch of TGR.

In this study, as stated above, there were eight parameters in the regression equation of Dong Pingbar group and three parameters in 0# enclosure group equation respectively (Table 5), which indicated that Chl-*a* was under the influence of many parameters in the natural waters of the Daning River of TGR. However, the parameters decreased greatly in 1#, 2# and 3# enclosures with changing shade material, and the WT and LI became major influencing factors on Chl-*a* (Table 5). Further study showed that a power exponent relationship between Chl-*a* and light intensity in all groups, that is Chl-$a = K(\mathrm{LI})^n$ (Table 7). In addition, the 2# group contained the largest coefficient of determination ($R^2 = 0.599$, $p = 0.000$), which indicated that there was a close relationship between Chl-*a* and LI. In other words, too high (0# and 1# groups) and too low LI (3# group) were both disadvantageous for algal growth. Based on the results of the current study, it was determined that LI may be the most important factor of algal growth.

4 Conclusions

Results from this study suggest were obtained under the same water quality and hydrodynamic conditions in the enclosure experiment, that is almost neutral and alkalescent water, high nitrogen and phosphate concentrations, and low potassium permanganate index values. The LI, Chl-*a*, DO and WT in the enclosures and the surrounding water all decreased gradually from 0.5 to 5.0 m underwater. In addition, the investigation on Chl-*a*, algae species and density all indicate that the suitable range of algal growth was about 0.5 m underwater.

Based on our findings, too high and too low LI were both disadvantageous to algal growth, and the function together with suitable temperature and LI and ample light application time resulted in algal blooms under the same water quality and hydrodynamic conditions. In addition, when Chl-*a* was at the high level, LI varied between 345 and 4390 lux at 0.5 m underwater and between 558 and 7450 lux at the surface above water, and WT was from 25.6 to 26.5°C.

Correlation analysis showed that LI and WT changed due to shading function, and their changes had no influence over DO. In addition, the pH of the water reduced gradually with algae from growth to death. Further regression analysis demonstrated that Chl-*a* was under the influence of many parameters in the natural waters of Daning River of TGR, but the parameters decreased greatly with

changing shade material. The power exponent relationship between Chl-*a* and light intensity in all groups, Chl-*a* = $K(\mathrm{LI})^n$, was clarified.

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