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# Influence Factors Analysis to Chlorophyll *a* of Spring Algal Bloom in Xiangxi Bay of Three Gorges Reservoir

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## Abstract

To study the relationship between environmental variables and chlorophyll *a* of spring algal bloom in Xiangxi Bay of Three Gorges Reservoir, stepwise multiple binomial regression and grey relative analysis methods were adopted. In surveys, 13 stations have been investigated and 143 samples were collected weekly from March 4 to May 13 in 2007. The study shows environmental variables (turbidity, total nitrogen, dissolved oxygen, total phosphates and silicate) are key factors during algal bloom. The grey relative values and their permutation indicated that turbidity was the most important factor and had comprehensive effect on chlorophyll *a*. The more number of interactive variables is found to be an indication of biochemical activity during spring algal bloom in Xiangxi Bay such as DO×TN, Turb×TP and so on. There was good linear relationship between chlorophyll a and the interaction of DO with TN ( $R = 0.9192$ , $P = 0.0001$ ).The interaction of nutrients (TP×TN, TP×$SiO_4$, TN×$SiO_4$) had significant influence to chlorophyll *a* and probably determined the inter-specific competition at different nutrient concentrations.

**Keywords:** Stepwise Multiple Binomial Regression, Grey Relative Analysis, Chlorophyll *a*, Environment Variables, Algal Bloom, Xiangxi Bay

## 1. Introduction

Biomass of phytoplankton in terms of the concentration of chlorophyll *a* is one of the most widely accepted methods in the study of biological production as it indicates total plant material available in the water at primary level of food chain [1]. Hence the growing and declining condition of algal bloom can be described by the spatial and temporal variation of chlorophyll *a*. There are many study methods to the relationship between chlorophyll *a* and physicochemical factors such as stepwise multiple regression analysis [2], grey relative analysis [3] and artificial neural network [4]. Chlorophyll *a* can be related to the environmental parameters by means of linear regression, though it provides only the prediction efficiency of a single factor at a time [5–7]. But the algal bloom is the multivariate interaction and nonlinear process. So a number of factors jointly controlling the bioactivities are to be considered.

Grey theory can reflect the dynamic state of data and has been broadly applied in the last decade since Deng Julong suggested the division of systems information to white, grey and black [8]. The systematic analytical method of grey theory was used to study the relationship between biomass of *Noctiluca scientillans* Macartney or *Prorocentrum sigmoides* Bohm (two red tide organisms) and various physicochemical factors of seawater [9,10].

Recently the relationship between chlorophyll *a* and environmental factors in Xiangxi Bay of Three Gorges Reservoir form March to April in 2005 were reported [6]. They showed that ecological factors (including total nitrogen, total phosphorus, water temperature, transparency and dissolved oxygen) had significant impact on the concentration of chlorophyll *a* using correlation analysis and linear regression method. But the multivariate interaction and nonlinear process in the algal bloom were not considered in the previous work. So this present paper aims to study: (1) controlling and interactive factors of chlorophyll *a*, (2) nonlinear interrelationship between physicochemical parameters and chlorophyll *a* of spring algal bloom in Xiangxi Bay. In order to achieve this, stepwise multiple binomial regression method and grey relative analysis are adopted.

## 2. Materials and Methods

### 2.1. Area Description

The Three-Gorge Dam (TGD) in China is the world's largest dam, measuring 2335 m long and 185 m high, and the reservoir created by it will have an area of 1080 $km^2$ in 2009 [11]. The Xiangxi River, which lies 38 km upstream from the Dam, is the largest tributary in the Hubei portion of Three-Gorge Reservoir (TGR). This river is 94 km long with a watershed of 3099 $km^2$ (between 110°25′and 111°06′E long., 30°57′and 31°34′N lat.) [12]. With impoundment of TGR, the downriver stretch of Xiangxi River was inundated and Xiangxi Bay was formed. The water level in the Xiangxi River has increased 40 m and the water flow velocity has dropped from the original 0.43-0.92 m/s [13] to 0.0020-0.0041 m/s [14]. So when water temperature increased in spring, there were algal blooms with prolonged retention time and high nutrient concentrations in Xiangxi Bay. *A. Formosa*, *C. acuta* and *C. ovata* were the dominant species.

### 2.2. Sampling and Analysis

Water samples were collected at 13 stations in Xiangxi Bay (Figure 1). Stations X0-X11 are on the Xiangxi River. Station GL is located at the downstream of Gaolan River, which is the largest tributary of the Xiangxi River. Samplings were performed weekly from March 4 to May 13, 2007. Water samples were collected at 0.5 m depth from surface in the middle of the river using a 5-L Niskin sampler (Hydrobios-Kiel). Water temperature (WT), dissolved oxygen (DO), pH, turbidity (Turb) were recorded in situ using multi-parameter water quality analyzer (Hydrolab DS5). Total phosphates (TP), phosphate ($PO_4$), total nitrogen (TN), ammonium nitrogen ($NH_4$), nitrate ($NO_3$), silicate ($SiO_4$) were determined in the laboratory using State Environmental Protection Administration (SEPA) standard methods [15]. For chlorophyll *a* (Chl.*a*) analysis, samples filtered through Whatman GF/F filters were extracted with cold 90% acetone and estimated by spectrophotometer [16].

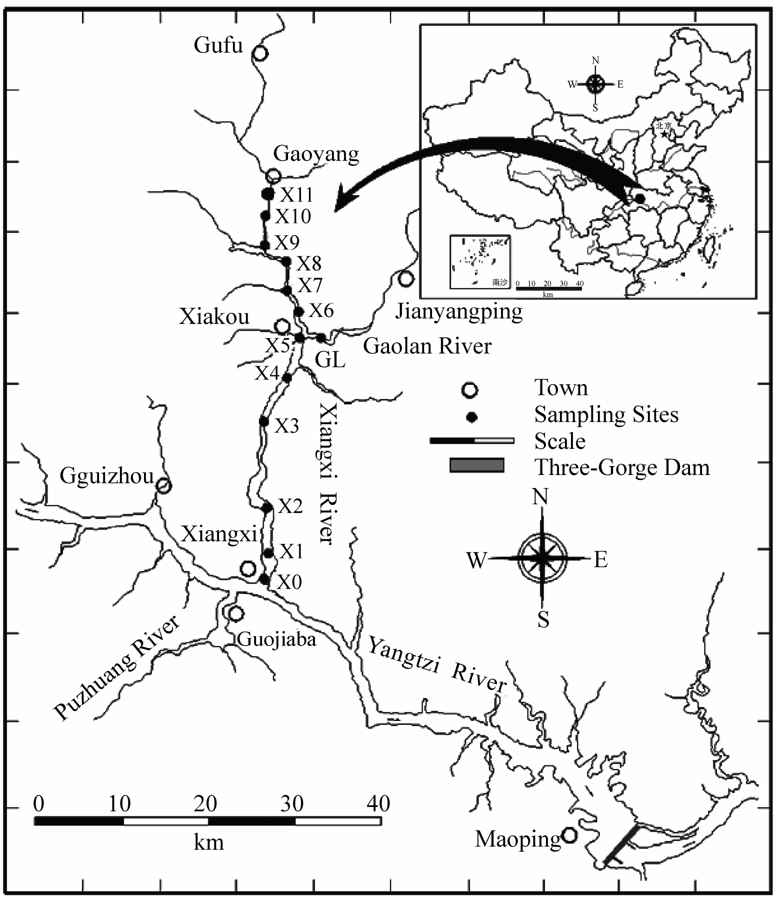


**Figure 1. Sampling stations in Xiangxi Bay.**

### 2.3. Statistical Analysis Using Stepwise Multiple Regression

Method of choosing the minimal set of environmental variables that can explain the variation in the affected parameter [17] was adopted earlier. A modern approach to explore the possible influence of various environmental variables on phytoplankton dynamics is the application of a multivariate statistical analysis [18]. These methods are widely used in ecological studies and have proved to be useful for understanding interactions between ecological factors that influence phytoplankton production. In this study, an attempt is made to include the individual factors, second order and interaction effects of the environmental parameters viz: WT (℃), DO (mg/L), pH, Turb (NTU), TP (mg/L), $PO_4$ (mg/L), TN (mg/L), $NH_4$ (mg/L), $NO_3$ (mg/L) and $SiO_4$ (mg/L) to relate chlorophyll *a* concentration (mg/m$^3$) in the predictive model. A stepwise multiple regression analysis is applied using phytoplankton (Chl.*a*) as the dependent variable, while individual, second order and interaction effects of the above listed environmental parameters as the independent variables, to examine the controlling role of any particular parameter or group of parameters on phytoplankton biomass.

### 2.4. Grey Relative Analysis

Based on the above investigation, chlorophyll *a* concentration (mg/m$^3$) in Xiangxi Bay was used as the analyzed sequence $\{X_0(k)|k=1,2,\cdots,N\}$, where sampling number $N=143$, and 10 factors including WT (℃), DO (mg/L), pH, Turb (NTU), TP (mg/L), $PO_4$ (mg/L), TN (mg/L), $NH_4$ (mg/L), $NO_3$ (mg/L) and $SiO_4$ (mg/L) were to be regarded as comparative sequences or subsequences $\{X_j(k)|k=1,2,\cdots,N\}$ $(j=1,2,\cdots,10)$. The calculation method [19] of grey system relative degree is as follows:

All the sequences are initiated for making them comparable. Let the analyzed sequence be:

$$\{Y_0(k)|k=1,2,\cdots,N\}=\{Y_0(1),Y_0(2),\cdots,Y_0(N)\}=\left\{\frac{X_0(1)}{M_0},\frac{X_0(2)}{M_0},\cdots,\frac{X_0(N)}{M_0}\right\} \quad (1)$$

where $M_0=\frac{1}{N}\sum_{k=1}^{N}X_0(k)$

So the comparative sequences are:

$$\{Y_j(k)|k=1,2,\cdots,N\}=\{X_j(k)/M_j|k=1,2,\cdots,N\}(j=1,2,\cdots,10) \quad (2)$$

where $M_j=\frac{1}{N}\sum_{k=1}^{N}X_j(k)$

Let $\zeta_i=\{\zeta_i(k)|k=1,2,\cdots,N\}(i=1,2,\cdots,10)$ be a relative coefficient between the analyzed sequence $\{Y_0(t)\}$ and the comparative sequence $\{Y_j(t)\}$, which is called the grey relative coefficients. Then

$$\zeta_i(k)=\frac{\underset{k}{Min}\Delta_i(k)+\underset{k}{Max}\Delta_i(k)}{\Delta_i(k)+\rho\underset{k}{Max}\Delta_i(k)} \quad (i=1,2,\cdots,10;k=1,2,\cdots,N) \quad (3)$$

where $\Delta_i(k)=|Y_0(k)-Y_i(k)|$ and $\rho(0<\rho<1)$ is a distinguished coefficient. Here we take it as $\rho=0.1$. Let

$$\gamma_i=\frac{1}{N}\sum_{k=1}^{N}\zeta_i(k) \qquad (i=1,2,\cdots,10) \quad (4)$$

where $\gamma_i$ is a relative degree between the analyzed sequence $\{Y_0(t)\}$ and the comparative sequence $\{Y_j(t)\}$.

## 3. Results

Using stepwise multiple binomial regression method, the "optimal" empirical mode of multiple binomial regression to chlorophyll *a* of spring algal bloom in Xiangxi Bay is obtained as follows:

$$Chl.a=40.1878-12.5897DO+0.5767(DO)^2+3.2052DO\times TN-1.2818Turb\times TP-58.9301TP\times TN+34.9789TP\times SiO_4-3.9612TN\times SiO_4$$
$$(R=0.7780,\ S=14.8202,\ F_{7,135}=29.5654,\ P=0.0001,\ n=143) \quad (5)$$

Partial correlation coefficient, t test value and p-value of independent variables in Equation (5) are presented in Table 1. All p-value of independent variables are less than 0.05.

The grey relative values between the analyzed sequence and subsequences for samples of 13 stations were calculated. The results of relative values are listed in Table 2, and the results of their permutation are in Table 3.

## 4. Discussion

The stepwise multiple regression and grey relative analysis show the environmental variables (Turb, TN, DO, TP, $SiO_4$) are more important and can reflect the

**Table 1. Partial correlation coefficient, t test value and p-value of independent variables in Equation 5.**

| independent variables | partial correlation coefficient | t test value | p-value |
|---|---|---|---|
| DO | -0.5510 | 7.6714 | 0.0001 |
| $(DO)^2$ | 0.6519 | 9.9881 | 0.0001 |
| DO×TN | 0.3521 | 4.3705 | 0.0001 |
| Turb×TP | -0.2051 | 2.4342 | 0.0162 |
| TP×TN | -0.2239 | 2.6698 | 0.0085 |
| TP×$SiO_4$ | 0.4127 | 5.2644 | 0.0001 |
| TN×$SiO_4$ | -0.2720 | 3.2847 | 0.0013 |

**Table 2. Grey relative values between chlorophyll *a* and physicochemical factors.**

| Station | WT | DO | pH | Turb | TP | $PO_4$ | TN | $NH_4$ | $NO_3$ | $SiO_4$ |
|---|---|---|---|---|---|---|---|---|---|---|
| X0 | 0.3512 | 0.3461 | 0.3351 | 0.3434 | 0.3663 | 0.3450 | 0.3942 | 0.3587 | 0.3289 | 0.3211 |
| X1 | 0.4094 | 0.4540 | 0.4107 | 0.4859 | 0.4917 | 0.4151 | 0.4317 | 0.4293 | 0.4259 | 0.4510 |
| X2 | 0.5068 | 0.5144 | 0.5198 | 0.5808 | 0.5435 | 0.5179 | 0.5115 | 0.4953 | 0.4853 | 0.5288 |
| X3 | 0.3985 | 0.4413 | 0.3921 | 0.4173 | 0.3826 | 0.3570 | 0.4216 | 0.3717 | 0.3692 | 0.4032 |
| X4 | 0.4395 | 0.4843 | 0.4415 | 0.4440 | 0.4034 | 0.4071 | 0.4702 | 0.4044 | 0.4375 | 0.4551 |
| X5 | 0.4923 | 0.4948 | 0.4996 | 0.5399 | 0.4995 | 0.4827 | 0.5304 | 0.4612 | 0.5109 | 0.5188 |
| GL | 0.3717 | 0.4189 | 0.3403 | 0.3754 | 0.3935 | 0.3781 | 0.3497 | 0.3568 | 0.3541 | 0.3582 |
| X6 | 0.3556 | 0.4084 | 0.3472 | 0.3997 | 0.3921 | 0.3936 | 0.4077 | 0.3449 | 0.3524 | 0.3574 |
| X7 | 0.3963 | 0.3936 | 0.4036 | 0.4073 | 0.3662 | 0.3409 | 0.4640 | 0.3448 | 0.3422 | 0.3749 |
| X8 | 0.4096 | 0.4454 | 0.4045 | 0.4503 | 0.4545 | 0.4476 | 0.4139 | 0.4050 | 0.4037 | 0.4262 |
| X9 | 0.4265 | 0.3819 | 0.4578 | 0.4045 | 0.4213 | 0.3977 | 0.4399 | 0.3629 | 0.3750 | 0.4445 |
| X10 | 0.4007 | 0.3861 | 0.4374 | 0.3825 | 0.4006 | 0.4084 | 0.3808 | 0.3817 | 0.3528 | 0.3792 |
| X11 | 0.3592 | 0.3394 | 0.3779 | 0.3825 | 0.3867 | 0.3757 | 0.3686 | 0.4027 | 0.3976 | 0.3530 |

**Table 3. Averages and permutation of the grey relative values from 13 stations.**

| | WT | DO | pH | Turb | TP | $PO_4$ | TN | $NH_4$ | $NO_3$ | $SiO_4$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Average | 0.4090 | 0.4237 | 0.4129 | 0.4318 | 0.4232 | 0.4051 | 0.4296 | 0.3938 | 0.3950 | 0.4132 |
| Permutation | 7 | 3 | 6 | 1 | 4 | 8 | 2 | 10 | 9 | 5 |

change of chlorophyll *a* concentration of spring algal bloom in Xiangxi Bay.

Based on grey relative analysis, Turbidity was the most important factor in the algal bloom and had comprehensive effect on chlorophyll a. As the low turbidity value chlorophyll *a* was in high level (Figure 2) because light illuminance under clear water was high and beneficial to phytoplankton photosynthesis [20]. When it rained from April 15 to April 22 in Xiangxi Bay, turbidity and silt increased, light illuminance under water decreased. Meanwhile, nutrients such as phosphates were adsorbed by silt in the river (interactive factor Turb×TP was included in Equation 5). So algal bloom declined.

Nitrogen entering aquatic systems arises from a variety of sources that include point and non point source pollution, biological fixation of gaseous nitrogen and the deposition of nitrogen oxides and ammonium [21]. Mean TN of spring algal bloom in Xiangxi Bay was $1.1289 \pm 0.4175$ mg/L with a minimum and maximum concentration of 0.3170 and 2.7890 mg/L respectively. Chlorophyll *a* of spring algal bloom had significant negative correlation with TN (Spearman $r = -0.18$, $n = 143$, $p < 0.05$), $NO_3$ (Spearman $r = -0.28$, $n = 143$, $p < 0.01$). Meanwhile TN had significant negative correlation with DO (Spearman $r = -0.32$, $n = 143$, $p < 0.01$) and there was good linear relationship between chlorophyll *a* and the interaction of DO with TN (DO×TN) (Figure 3):

$$Chl.a = 0.062721 + 1.014050(DO \times TN)$$

$$(R = 0.9192,\ S = 9.0913,\ P = 0.0001,\ n = 143) \quad \textbf{(6)}$$

These data indicate nitrogen transformation by DO

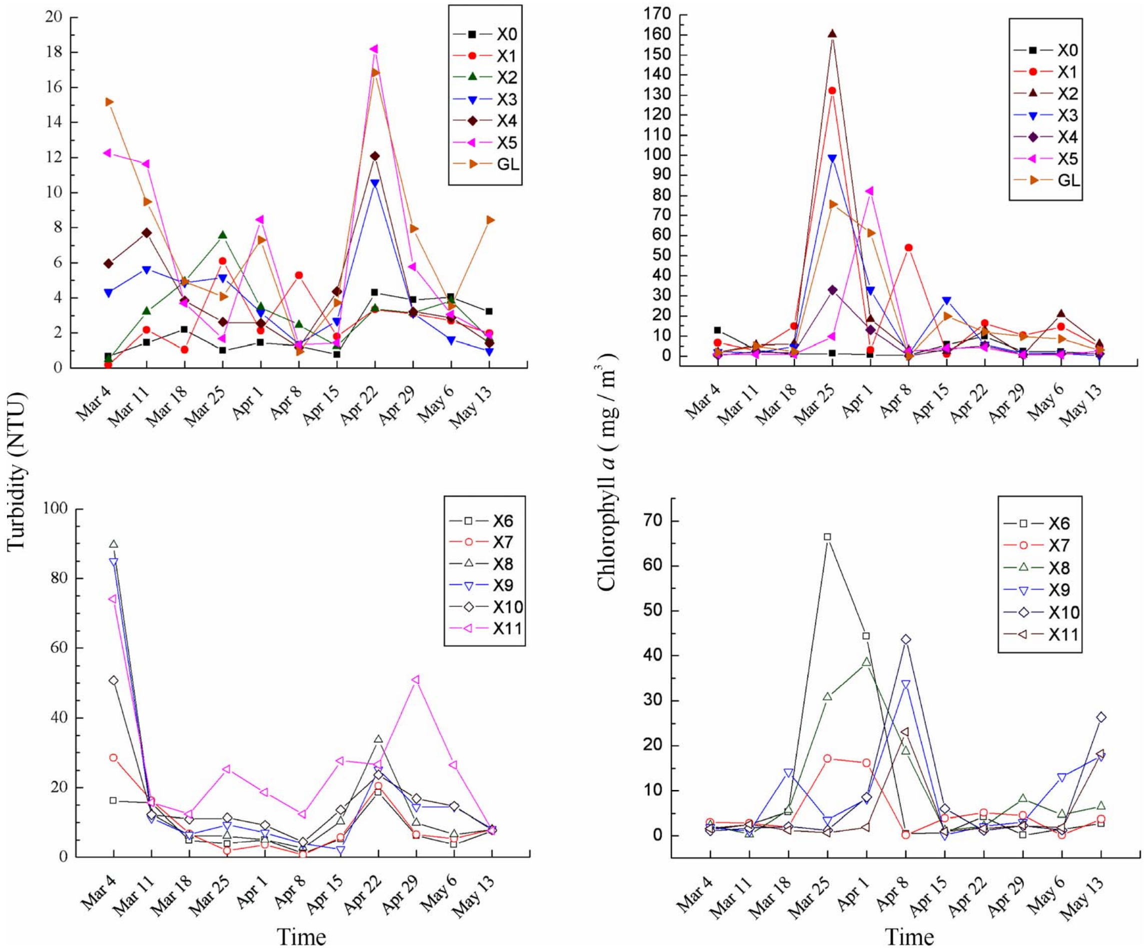


**Figure 2. Temporal and spatial change of turbidity and Chl.*a* in different sampling stations of Xiangxi Bay.**

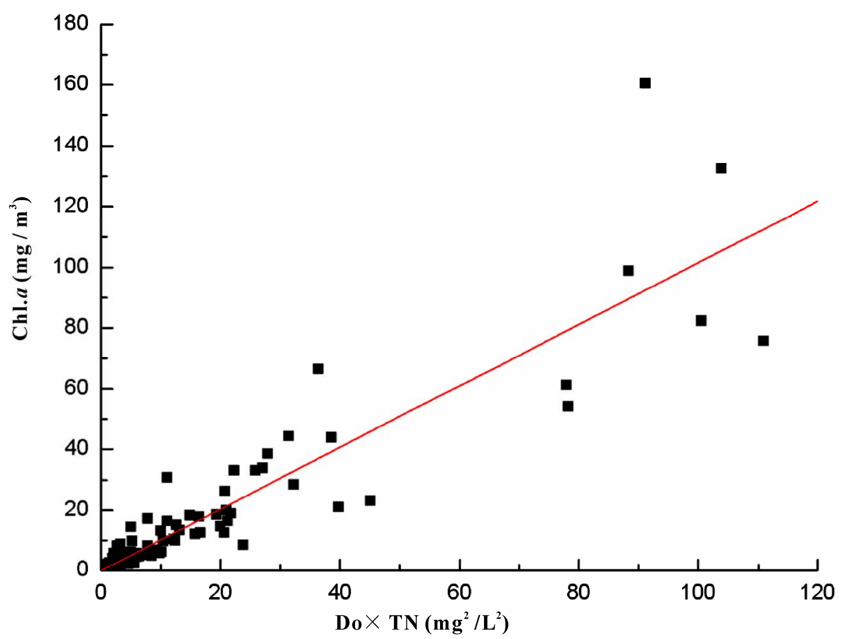


**Figure 3. The relationship between chlorophyll *a* and DO×TN in Xiangxi Bay.**

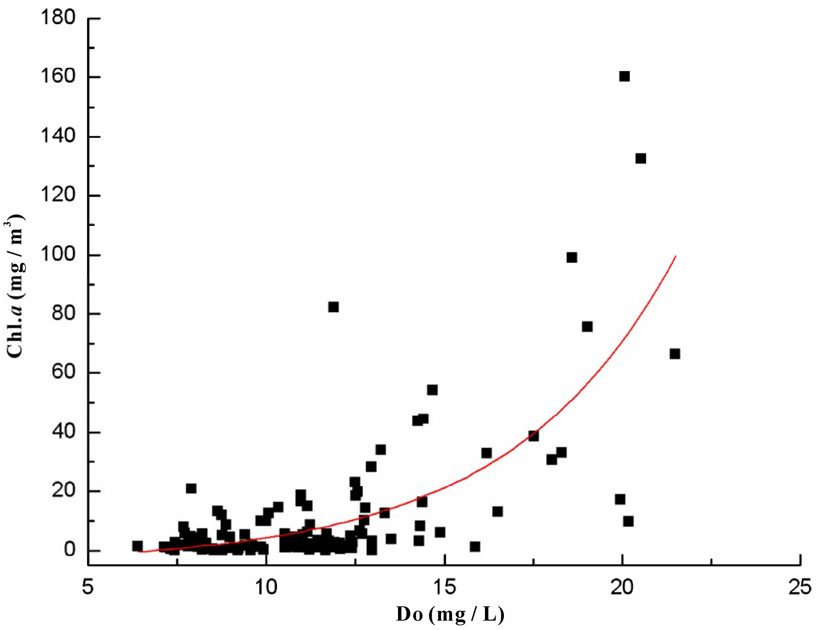


**Figure 4. The relationship between chlorophyll *a* and dissolved oxygen in Xiangxi Bay.**

plays an important role in phytoplankton growth and the soluble nutrients may be effectively uptake by phytoplankton.

The relationship between chlorophyll *a* and dissolved oxygen was nonlinear (Figure 4), which regression model was as follows:

$$Chl.a = -4.1969 + 0.9856\exp(0.2166DO)$$

$$(R = 0.7141,\ S = 16.1750,\ P = 0.0001,\ n = 143) \quad \textbf{(7)}$$

It was due to the increase of oxygen which was released during phytoplankton photosynthesis [22] and the decrease of oxygen which was consumed by organic matter [23].

Total phosphate and silicate were also important factors to chlorophyll *a*. Mean values of TP and $SiO_4$ in Xiangxi Bay were $0.1958 \pm 0.1095$ mg/L and $3.7313 \pm 1.0258$ mg/L respectively during spring algal bloom. The phosphate load was high and increased from downstream to upstream because there were phosphate mines and phosphate plants in the upstream of Xiangxi River [24]. Diatoms were the dominant species during the later stage of algal bloom and silicate was necessary to diatoms growth. The cooperate interaction of nutrients (TP×TN, TP×$SiO_4$, TN×$SiO_4$) had significant influence to chlorophyll *a* during spring algal bloom based on stepwise multiple binomial regression and probably determined the inter-specific competition at different nutrient concentrations, because their intakes were species specific [25]. So the relationship between different algal species densities and different nutrient concentrations would be studied in the future work.

## 5. Conclusions

The study using stepwise multiple regression and grey relative analysis method shows the significant influence of environmental variables (turbidity, total nitrogen, dissolved oxygen, total phosphates and silicate) and their interactions on the production of chlorophyll *a*. The grey relative values and their permutation indicated that turbidity was the most important factor and had comprehensive effect on chlorophyll *a*. The more number of interactive variables is found to be an indication of biochemical activity during spring algal bloom in Xiangxi Bay such as DO×TN, Turb×TP and so on. There was good linear relationship between chlorophyll *a* and the interaction of DO with TN (DO×TN). The interaction of nutrients (TP×TN, TP×$SiO_4$, TN×$SiO_4$) had significant influence to chlorophyll *a* and probably determined the inter-specific competition at different nutrient concentrations.

## 6. Acknowledgements

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