Assessment and Prediction on the Eutrophic State of a Drinking Water Source☆

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Abstract: To evaluate the eutrophic state of Xiliu Lake (a water source for Zhengzhou city) and establish prediction system to monitor and predict the eutrophic condition of this water resource. Environmental factors including water temperature (WT), secchi depth (SD), water depth (WD), chemical oxygen demand (COD_{Mn}), total nitrogen (TN), total phosphorus (TP), chlorophyll-a (Chla), algae cell density (ACD) and cyanophyta cell density (CCD) were measured continuously in two sampling sites that were selected in Xiliu Lake. Trophic level index (∑) (TLI(∑)), linear correlation and stepwise multiple regression with a significant-value cut-off of α=0.05 were used to analyze the data. The result showed that the TLI(∑) of Xiliu Lake increased with seasonal changes. Three regression equations of standardized Chla, standardized ACD and standardized CCD were obtained respectively. Tests on these regression equations showed that there was a good correlation between practical value and predictive value of standardized Chla. The correlations for standardized ACD and CCD were even better. In a conclusion, the nutritive condition of Xiliu Lake was eutrophic. A prediction system was established for monitoring the eutrophic condition of surface water through using the three regression equations of standardized Chla, standardized ACD and standardized CCD, which can be used to predict the trend of Chla in Xiliu Lake within a certain range.
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1. Introduction

With the advance in industry and agriculture as well as the increase of population, the eutrophic condition of polluted water body becomes more and more serious. It has been reported that different eutrophication levels exist in 53%, 28%, 48%, 41% and 54% of lakes in Europe, Africa, North America, South America and Asian Pacific area respectively[1]. The eutrophic condition of freshwater in China has been very seriously since 1990 including Yangtze River, Yellow River, Taihu Lake, Chaohu Lake and so on[2-4].

Polluted by waste water containing nitrogen and phosphate, the water quality becomes worse, and the ecological balance is destroyed, which further leads to reproduction of algae that excessively consumes oxygen in water and makes fishes and planktons die due to lack of oxygen. In turn, their bodies are decomposed and pollute the water again. Given such a serious environmental challenge, it is necessary to establish novel scientific evaluation methods for managing and protecting water environment.

So far, most studies have focused on algae and toxins, but there has been no study about the relationships between proliferation of algae and environmental factors in Henan. Therefore, we decided to carry out a study on Xiliu Lake that is the water resources of Zhengzhou, which will provide crucial information for safe water supply in Zhengzhou. Currently, the main methods for evaluating the eutrophic state of lake include trophic state index (Carlson index), amended trophic state index and comprehensive nutrition state index (TLI(∑)). TLI(∑) is simple and convenient, scientifically sound and easily mastered, and therefore we adopted this index to analyze the trophic state of Xiliu Lake. This study will provide crucial information for safe water supply in Zhengzhou.

2. Material and Methods

2.1 Study Sites

Xiliu Lake in Zhengzhou was formed by Yellow River flowing through sedimentation basin many decades ago. The lake has a surface area of 150 ha, and it is the major water source for residents in Zhengzhou city.

As for sanitation state surrounding Xiliu Lake, within the range of 2,000 m, there is a shelter belt in the west of sampling site NO.1, while there are shelter belts in both west and east sides of sampling site NO.2, but these shelter belts do not work well. As a result, there are many pollution sources including agricultural pollution, soil losses, rubbish, and sewage.

2.2 Sampling procedure

Two sampling sites were selected in Xiliu Lake. The first one was at the entrance of a storage pool of Shiyuan water factory, and the second was 1,000 m away from the storage pool. The monitoring time was from March to October, and the sampling time was at 8:00～9:00Am. During the sampling, 7.5L water was collected at 5 m below water surface with a collecting device of 2.5L, and then put into polythene bottles and glass bottles quickly. Meanwhile, air temperature was measured.

2.3 Detected items and methods

The following items were measured in the study: water temperature (WT), secchi-depth (SD), water depth (WD), chemical oxygen demand (COD_{Mn}), total nitrogen (TN), total phosphorus (TP), chlorophyll-a (Chla), algae cell density (ACD), and cyanophyta cell density (CCD). WT was measured with a deep water thermometric (Shanghai Medical Instrument Factory, China). SD and WD were measured with Saishi disc[5]. COD_{Mn} was measured with the method of acidic potassium permanganate [5]. TN was measured with the method of alkaline potassium persulphate digestion UV-spectrophotometric[6]. TP was measured with the method of ammonium molybdate spectrophotometric[7]. Chla was measured with the method of spectrophotometric. ACD and CCD were measured by counting the number of blood corpuscle discs.

2.4 Statistical analyses

Trophic level index (Σ) (TLI[Σ]), linear correlation and stepwise multiple regression analyses were used, and a significant difference was defined when $\alpha = 0.05$. Comprehension eutrophic state index was defined as in previous studies [8,9]. The data were analyzed with Excel and SPSS (version 11.0). The dataset of the five water-quality indexes at the two sampling sites in Xiliu Lake were expressed as mean ± standard deviation, and the evaluation criterion was the III standard according to GHZB1-1999 and GB3838-2002 (Environmental Quality Standard for Surface Water), (III standard as the abbreviation in the following text). SD showed a decreasing tendency with the increase of water pollution, and the amount of exceeding the standard was calculated with the formula: (certified value – mean value)/ certified value; the constituent ratio of dominate algae was expressed as pie chart; Chla, ACD, CCD were transformed by ln(X+1), then the multiple-linear regression analysis was performed between the environmental chemical-physical factors and ln(X+1). The parameters for the regression equations were as follows: statistic value of Durbin-Watson was about 0～4, residual error value interdependency was about 2, condition index < 30, mean square expansion factors of independent variable $\ngtr 10$, tolerance of independent variable $\nless 0.1$, multidimensional characteristic root $\neq 0$.

3. Results

3.1 The Eutrophic State of Xiliu Lake

Table 1 shows the changes of TLI(Σ) in three seasons. In spring, TLI(Σ) at the two sites were 48.43 and 49.74 respectively, which were close to the maximum value of mesotrophic state (50). In summer, TLI(Σ) were 58.04 and 58.91 respectively, which were close to the maximum value of slight eutrophic state (60). In autumn, TLI(Σ) were 62.43 and 60.33 respectively, which exceeded to the limit value of medium eutrophic state. Thus, the nutritive state of Xiliu Lake varied from the maximum of mesotropher, the maximum of light eutropher to the minimum of middle eutropher. These results suggested that TLI(Σ) of Xiliu Lake increased with seasonal changes.

Table 1.Trophic State of Two Sampling Sites and Xiliu Lake in Different Seasons

Sampling sites		TLI					TLI(Σ)	trophic state
		Chla	TP	TN	SD	COD_{Mn}		
Spring	NO.1	12.32	8.65	11.21	9.05	7.20	48.43	Mesotrophic state
	NO.2	13.40	8.27	11.69	8.95	7.43	49.74	Mesotrophic state
Summer	NO.1	17.30	10.06	11.41	10.01	9.26	58.04	Oligotrophic state
	NO.2	17.80	9.61	11.46	10.56	9.48	58.91	Oligotrophic state
Autumn	NO.1	19.49	11.79	11.56	10.32	9.26	62.43	Mesotrophic state
	NO.2	18.80	9.94	11.77	10.87	8.95	60.33	Mesotrophic state
Spring		12.91	8.46	11.46	8.98	7.32	49.14	Mesotrophic state
Summer	Xiliu	17.56	9.86	11.44	10.27	9.41	58.55	Oligotrophic state
Autumn	lake	19.17	11.02	11.68	10.61	9.11	61.58	Mesotrophic state

3.2 Stepwise multiple linear regression between environmental factors and standardized Chla, ACD and CCD

Standardized Chlα has a positive correlation with standardized WT, COD_{Mn} and TP, but it has a negative correlation with SD (Table 2). The equations are as follows:

ln(Chla + 1) = 0.390 + 0.134×WT (R = 0.912, F = 112.967, P < 0.01)
ln(Chla + 1) = -0.442 + 0.660 × COD_{Mn} (R = 0.853, F = 61.398, P < 0.01)
ln(Chla + 1) = 1.918 + 18.165 × TP (R = 0.669, F = 18.601, P < 0.01)
ln(Chla + 1) = 6.209 - 3.298× SD (R = 0.836, F = 53.556, P < 0.01)

Table 2. Linear Correlation Matrix between Standardized Chla and the Environmental Chemical-Physical Factors in Xiliu Lake

Item	WT	SD	COD_{Mn}	TN	TP	ln(Chla+1)
WT	1.000					
SD	-.812* *	1.000				
COD_{Mn}	.849* *	-.841* *	1.000			
TN	-.013	.135	.091	1.000		
TP	.521* *	-.566* *	.479*	.339	1.000	
ln(Chla+1)	.912* *	-.836* *	.853* *	.112	.669* *	1.000

*Note.**. P < 0.05; **. P < 0.01.

Table 3. Stepwise Regression Results of Standardized Chla and the Environmental Chemical-Physical Factors in Xiliu Lake

Site	Selected variance	Stepwise regression equation	coefficient of determination	F	P
NO.1	1 WT 2 TP 3 SD	$\ln(Chla+1)=1.905+9.450\times10^{-2}WT+4.533TP-1.240SD$	0.833	34.883	.000
NO.2	1 WT 2 TP	$\ln(Chla+1)=0.364+0.111WT+9.092TP$	0.896	95.120	.000
Xiliu lake	1 WT 2 TP 3 COD_{Mn}	$\ln(Chla+1)=-0.114+8.348\times10^{-2}WT+6.874TP+0.193\ COD_{Mn}$	0.900	62.674	.000

Table 3 shows stepwise regression equations of standardized Chla and the environmental chemical-physical factors in Xiliu Lake. It can be seen that at different sampling sites, the screening factors which have significantly positive correlation with standardized Chlα were different.

At sampling site NO.1, three factors were selected: WT and TP were the positive correlation factors, while SD was the negative correlation factor. At sampling site NO.2, two factors were selected: WT and TP were the positively correlated factors (P < 0.01 in regression equations). In Xiliu Lake, WT, TP and COD_{Mn} affected standardized Chla and they were selected (P < 0.01 in regression equation).

Fig. 1 shows the testing results based on the regression equations of standardized Chlα in Xiliu Lake. We calculated the predictive value by substituting the environmental factors of WT, TP and COD_{Mn} into the regression equation in Table 3. Then, the value was fit with the practical value. As shown in Fig. 1, the correlation between practical value and predictive value was better, so the regression equation can be used to predict the trend of Chla in Xiliu Lake within a certain range.

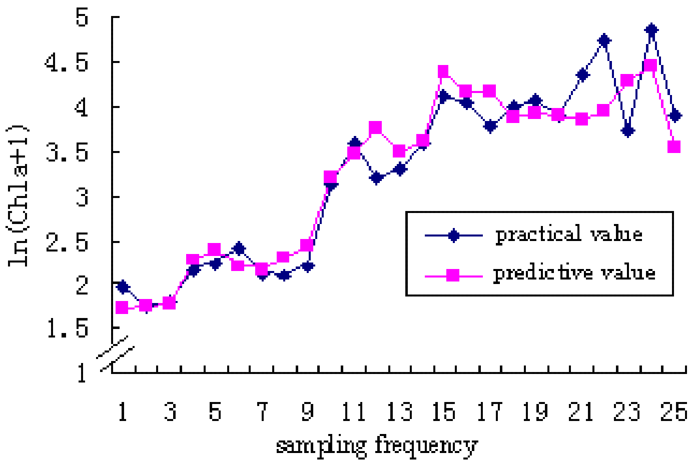

Figure 1. The Fitting Curve between the Practical Value and Predictive Value of Standardized Chla in Xiliu Lake.

3.3 Stepwise regression analysis of standardized ACD, CCD and the environmental chemical-physical factors

Table 4 shows the linear correlation matrix between standardized ACD, CCD and the environmental chemical-physical factors that we studied.

The relationships of standardized ACD and standardized COD_{Mn} with TP were positive; the relationships with SD and WD were negative. The regression equations were following:

ln(ACD + 1) = 4.719 + 0.182 × WT (*R* = 0.824, *F* = 48.612, *P* < 0.01)
ln(ACD + 1) = 6.514 + 28.512 × TP (*R* = 0.698, *F* = 21.892, *P* < 0.01)
ln(ACD + 1) = 12.945 - 4.838 × SD (*R* = 0.816, *F* = 45.966, *P* < 0.01)
ln(ACD + 1) = 19.247 - 5.298 × WD (*R* = 0.711, *F* = 23.466, *P* < 0.01)
ln(CCD + 1) = 1.293 + 0.295 × WT (*R* = 0.866, *F* = 69.071, *P* < 0.01)
ln(CCD + 1) = 4.307 + 44.674 × TP (*R* = 0.711, *F* = 23.460, *P* < 0.01)
ln(CCD + 1) = 13.973 - 7.123 × SD (*R* = 0.781, *F* = 35.869, *P* < 0.01)
ln(CCD + 1) = 23.438 - 7.894 × WD (*R* = 0.688, *F* = 20.627, *P* < 0.01)

Table 4. Linear Correlation Matrix between Standardized Algae Cell Density, *Cyanophyta* Cell Density and the Environmental Chemical-Physical Factors in Xiliu Lake

Item	WT	SD	WD	TN	TP	ln(ACD+1)	ln(CCD+1)
WT	1.000						
SD	-.812* *	1.000					
WD	-.633* *	.766* *	1.000				
TN	-.013	.135	-.004	1.000			
TP	.521* *	-.566* *	-.405*	.339	1.000		
ln(ACD+1)	.824* *	-.816* *	-.711* *	.045	.698* *	1.000	
ln(CCD+1)	.866* *	-.781* *	-.688* *	.068	.711* *	.978* *	1.000

*Note.**. *P* < 0.05; **. *P* < 0.01.

Tables 5 and 6 show stepwise regression equations of standardized ACD, CCD based on the environmental chemical-physical factors in Xiliu Lake.

As shown in Table 5, the screening factors that had significantly positively correlations with standardized ACD at the two sampling sites are different. At sampling site NO.1, three factors were selected: WT and TP were the positively correlated factors; while SD was the negatively correlated factor. At sampling site NO.2, two factors were selected: TP was the positively correlated factor, while WD was the negatively correlated factor (*P* < 0.01 in regression equation). In Xiliu Lake, both WT and TP were selected for standardized ACD (*P* < 0.01 in regression equation).

Table 6 shows that the same screening factors were significantly positively related with standardized CCD at both sampling sites, and these two factors (TP and WT) were selected (*P* < 0.01 in regression equation). For Xiliu Lake, WT and TP affected standardized CCD, and they were selected ($P < 0.01$ in regression equation).

Three regression equations of standardized Chla, standardized ACD and standardized CCD and the environment physical and chemical factors are as follows:

(1) $\ln(Chla + 1) = -0.114 + 8.348 \times 10 - 2 \times WT + 6.874 \times TP + 0.193 \times COD_{Mn}$, $P < 0.01$.
(2) $\ln(ACD + 1) = 4.524 + 0.140 \times WT + 15.071 \times TP$, $P < 0.01$.
(3) $\ln(CCD+1) = 1.004 + 0.232 \times WT + 22.364 \times TP$, $P < 0.01$.

After putting the environmental factors of WT and TP into the regression equation for Xiliu lake in Tables 5 and 6, the predictive value was gained, then the value was fit with the practical value. The result showed in Figure 2.

Table 5. Stepwise Regression Results of Standardized Algae Cell Density and the Environmental Chemical-Physical Factors in Xiliu Lake

Site	Selected variance	Stepwise regression equation	coefficient of determination	*F*	*P*
NO.1	1 WT 2 TP 3 SD	ln(ACD+1)=6.653+0.119WT+8.782TP-1.523SD	0.793	26.779	.000
NO.2	1 TP 2 WD	ln(ACD+1)=14.667+34.936TP-3.899WD	0.735	30.563	.000
Xiliu Lake	1 WT 2 TP	ln(ACD+1)=4.524+0.140WT+15.071TP	0.778	38.559	.000

Table 6. Stepwise Regression Results of Standardized *Cyanophyta* cell density and the environmental chemical-physical factors in Xiliu Lake

Site	Selected variance	Stepwise regression equation	coefficient of determination	*F*	*P*
No.1	1 WT 2 TP	ln(CCD+1)=1.404+0.231WT+14.603TP	0.811	47.349	.000
No.2	1 WT 2 TP	ln(CCD+1)=0.478+0.258WT+24.588TP	0.787	40.539	.000
Xiliu Lake	1 WT 2 TP	ln(CCD+1)=1.004+0.232WT+22.364TP	0.842	58.773	.000

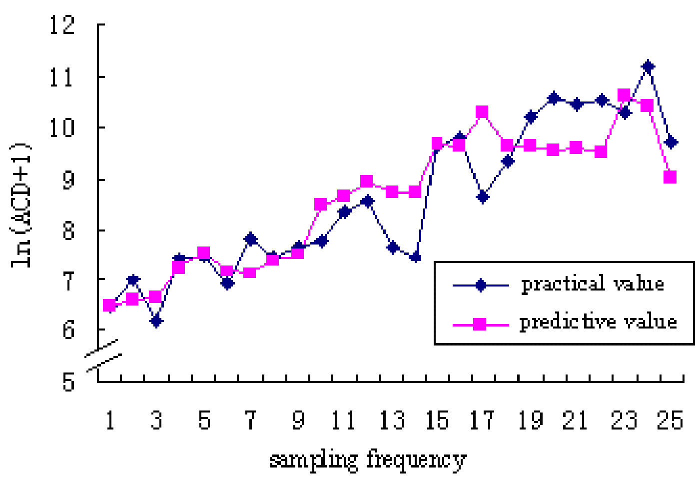

Figure 2. The Fitting Curve between the Practical Value and Predictive Value of Standardized Algae Cell Density in Xiliu Lake.

4. Discussions

4.1 Relationship between environmental factors and standardized Chla, ACD and CCD

Chla is an important pigment in plant photosynthesis, which represents the primary productive force and has been considered as a key parameter for biomass and capacity of plankton[10]. It has become a crucial biological index for monitoring eutrophic water quality. Some studies show that there is a good correlation between ACD and the concentration of Chla[11,12]. Suitable WT can promote the growth of algae, and the dominant algae varies with the change of WT[13]. SD is also a key environmental factor affecting Chla, ACD and CCD, because it directly influences illumination intensity that leads to the change of productive layers [14]. COD_{Mn} represents the content of organic materials oxidized by potassium permanganate. In general, the change of nutriment concentration has the same phase as that of organic contamination content, and there is a lot of organic contamination when the biomass is higher in water. Thus, the relationship between Chla and COD_{Mn} indicates the trend of cooperation between each other, but it can not show that the organic is the limiting factor for the algae growth [15].

As seen from the molecular formula of algae bioplasm ($C_{106}H_{263}O_{110}N_{16}P_1$), there are some N and P content given C, H and O, so the nutrition containing N and P is essential for the plankton growth. Some reports show that N and P are the determining factors that affect the growth of planktons: planktons tend to be P-restricted but not N-restricted [16-18]. Our results showed that TN did not affect Chla, ACD and CCD; and TP had significantly positive correlations with Chla, ACD and CCD.

We obtained the predictive equation for standardized Chla, ACD and CCD in Xiliu Lake. These equations indicated that the key factors affecting standardized Chla, standardized ACD and standardized CCD were WT, TP and COD_{Mn}, WT and TP, WT and TP, respectively. In order to validate these equations, we calculated the predictive values and compared it with the measured ones. We found that the curve fitting of predictive value and measured value of standardized Chla was good, and the curve fitting of predictive value and measured value of standardized ACD and CCD was even better.

Among the environmental factors in the predictive equations, TP and COD_{Mn} can be controlled by people, so it is critical in decreasing and controlling these two factors in order to prevent the eutrophication of Xiliu Lake.

4.2 Equation established between standardized ACD, CCD and the environmental chemical-physical factors

We observed significantly positive correlations of standardized Chla with WT, COD_{Mn} and TP, and significantly negative correlations with SD in Xiliu Lake. Through the stepwise multiple regression analysis, three significant correlated factors were selected at sampling site No. 1: WT and TP were the positively correlated factors; while SD was the negatively correlated factor. Two factors were selected at sampling site No. 2: WT and TP were the positively correlated factors. In Xiliu Lake, WT, TP and COD_{Mn} were the most significantly correlated factors with standardized Chla.

Significantly positive correlations were found between standardized ACD, CCD and WT, TP， and significantly negative correlations were found between standardized ACD, CCD and SD in Xiliu Lake. The stepwise multiple regression analysis on ACD showed that three significantly correlated factors were selected at sampling site No.1: WT and TP were the positively correlated factors, while SD was the negatively correlated factor. Two significantly correlated factors were selected at sampling site No.2: TP was the positively correlated factor, while SD was the negatively correlated factor. For Xiliu Lake, WT and TP were the most significantly correlated factors for standardized ACD. The stepwise multiple regression analysis on CCD showed that two significantly correlated factors were selected for both sampling sites: WT and TP were the positive correlated factors. For Xiliu Lake, WT and TP were the most significantly correlated factors for standardized CCD. The inspective results of three regressive equations showed that the coincidence of practical value and predictive value of the standardized Chla was good. And the coincidence of practical value and predictive value of the standardized ACD and CCD was better. The contents of Chla, ACD and CCD could be predicted by the multiple equations. The fitting of practical value and predictive value are relatively coincidence.

In a conclusion, this study established a prediction system for monitoring the eutrophic condition of surface water using three regression equations of standardized Chla, standardized ACD and standardized CCD based the environment physical and chemical factors. These regression equations can be used to predict the trend of Chla in Xiliu Lake within a certain range, which will provide crucial information for safe water supply in Zhengzhou.

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