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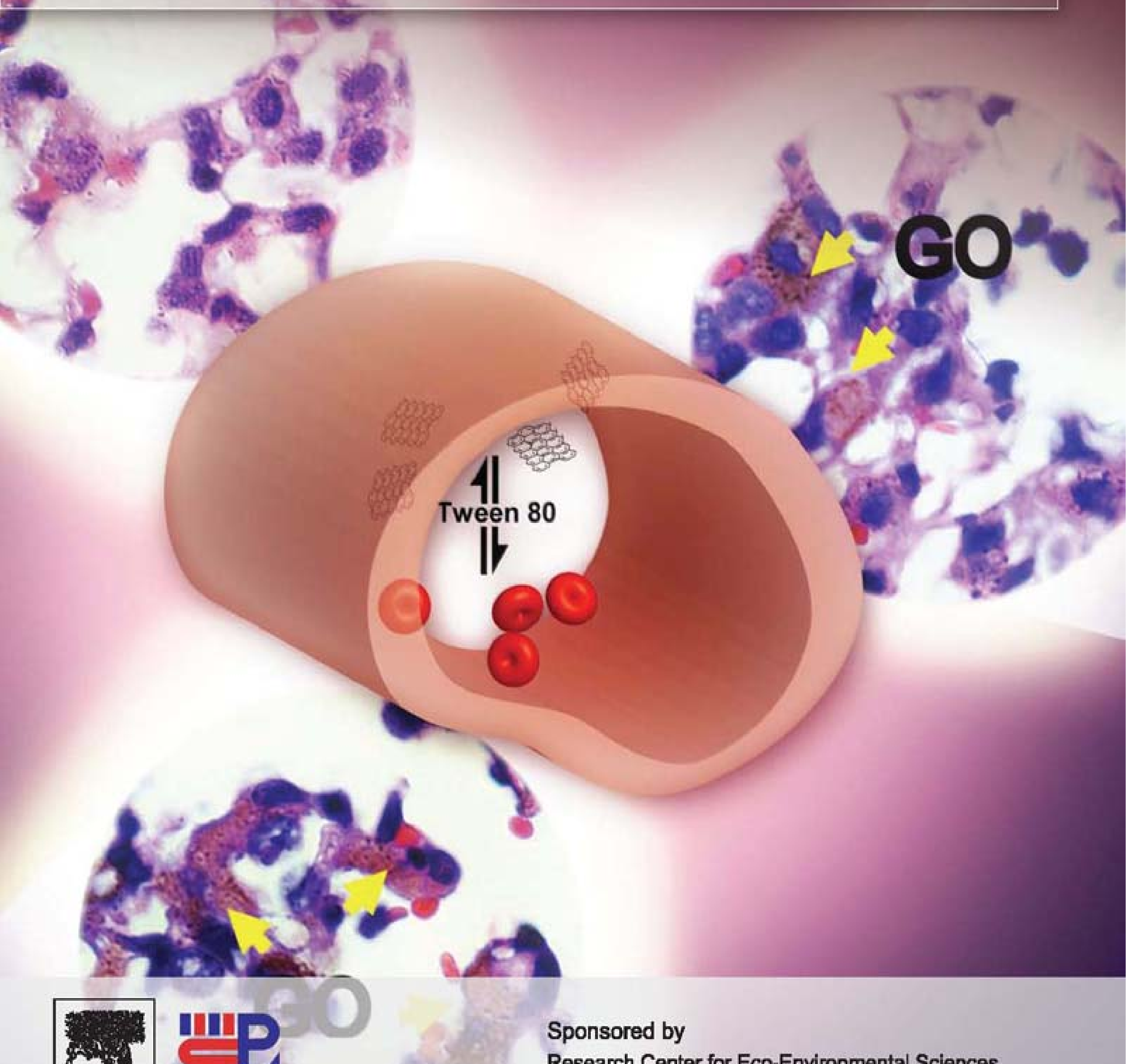

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Determining reference conditions for TN, TP, SD and Chl-*a* in eastern plain ecoregion lakes, China

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Abstract

Establishing the nutrient reference condition (baseline environmental condition) of lakes in an ecoregion is a critical consideration in the development of scientifically defensible aquatic nutrient criteria. Three methods were applied to determine reference conditions in the Eastern plain ecoregion lakes with respect to total phosphorus (TP), total nitrogen (TN), planktonic chlorophyll *a* (Chl-*a*) and Secchi depth (SD). The reference condition value for the lakes in the Eastern plain ecoregion by the trisection method is TP of 0.029 mg/L, TN of 0.67 mg/L, Chl-*a* of 3.92 mg/m^3, SD of 0.85 m, and the reference condition range by the lake population distribution approach is TP of 0.014–0.043 mg/L, TN of 0.360–0.785 mg/L, Chl-*a* of 1.78–4.73 mg/m^3, SD of 0.68–1.21 m. Additionally, empirical models were developed for estimating the reference Chl-*a* concentration and SD successfully for lakes in the Eastern plain ecoregion. Overall, the data suggest that multiple methods can be used to determine reference conditions and that in Eastern plain ecoregion lakes the reference condition corresponds to a mesotrophic status.

Key words: lake reference condition; lake population distribution approach; trisection method; model prediction

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Introduction

Reference conditions are a representation of ecological integrity, which can be defined as the ability to support and maintain a balanced, integrated, adaptive community of organisms having a species composition, diversity and functional organization comparable to that of the natural habitat of the region (Solheim, 2005; Karr, 1991). Ideally, reference conditions associated with nutrient-related variables are defined as the nutrient concentrations representing lake conditions in the absence of anthropogenic disturbance and pollution. However, because it can be argued that most lakes have been impacted by human activity to some degree, reference conditions realistically represent the least impacted conditions or what is considered to be the most attainable conditions (US EPA, 2000). The use of total phosphorus (TP), total nitrogen (TN), and chlorophyll *a* (Chl-*a*) concentrations and Secchi depth (SD) as nutrient-related measures of lake water quality are widely adopted around the world (e.g., US EPA, 1998a; Dodds et al., 2006; Carvalho et al. 2008; Poikane et al., 2010).

Several approaches have been suggested for delimiting reference conditions such as direct observation (data collection) of lakes (e.g., reference lake approach), paleolimnological reconstruction, model prediction and extrapolation, and expert judgment (US EPA, 1998b, 1998c; Paul and Gerritsen, 2002; European Communities, 2003; Bennion and Battarbee, 2007). Two statistically based approaches, the reference lake approach and lake population distribution approach, have been recommended by the US EPA (2000) to define a reference condition for any particular nutrient (e.g., TN, TP), within any particular ecoregion. The US EPA developed ambient reference conditions for TP, TN, Chl-*a*, and SD in the 14 aggregate nutrient ecoregions by the two approaches. Subsequently, states and tribes did a great deal of work on developing reference conditions and nutrient criteria, and some new approaches were proposed (e.g., Paul and Gerritsen, 2002; Heiskary and Wilson, 2005; Walker et al., 2007). Since the European Commission Water Framework Directive (EC, 2000) was promulgated, Member States have started to develop lake ecological status assessment systems, and

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finished setting TP and Chl-*a* as reference conditions for European lakes in different lake types and ecoregions (Cardoso et al., 2005; Carvalho et al., 2008; Poikane et al., 2010).

In recent years, some researchers have initiated studies on the methodology of nutrient criteria development in China, and a Regional Nutrient Criteria Research Plan was carried out in 2008 (Huo et al., 2009, 2010a, 2010b, 2012; Chen et al., 2010; Liu, 2011). The objectives of this study are to (1) test three techniques for determining reference conditions; (2) offer insight into the identification of the reference conditions and the development of appropriate criteria within the Eastern plain ecoregion, China.

1 Material and methods

1.1 Study area

The Eastern plain ecoregion is the east part of China (25°–35°N, 108°–122°E), situated in the warm temperature zone and subtropics, near the sea and ocean. The Eastern plain ecoregion has the highest density of lakes in China, and most of the lakes are shallow with a large surface area. Total lake surface area in this area is more than 22,900 km^2, amounting to 27.5% of all lake surface area in China (Jin et al., 1995). These lakes are mainly located in the Yangtze River Plain and Delta, partly in the Huaihe River Plain. The littoral zones of lakes consist of loose deposits which shift in shape due to both current and wave action. Due to this region having a long history of anthropogenic development, human economic activities have great influence on both the morphology of lakes and the water quality (Jin et al., 1990). The freshwater storage and water quality of lakes in the region is very important throughout the country and they supply the majority of available freshwater resources. Relevant goals for measures to keep the water resources in good ecological condition are needed in this region. However, relevant goals can only be achieved if we have defined the lake nutrient reference conditions.

1.2 Data sources and data quality

In defining the trophic status of lakes, nutrients such as TN and TP are generally described as driver variables and Chl-*a* and SD as response variables. Data for TP, TN, Chl-*a* and SD were collected from lakes across the Eastern plain ecoregion as part of the ambient monitoring network maintained by the Department of Environmental Protection of the Anhui, Hubei, Hunan, Jiangsu, Jiangxi and Zhejiang Provinces, China. A total of more than 107 water bodies were selected for this analysis, mainly from 1990 to 2008. Data were included from lakes that had at least three surveys (in three water periods) in separate years over this time interval. Approximately 30 water bodies were sampled on a rotational schedule as part of a fixed ambient water quality network. The remaining lakes were sampled as part of several synoptic surveys, special projects and other non-routine sampling efforts. The TP, TN, Chl-*a* and SD were measured according to the standard methods (EPA of China, 1989).

During the time period used for this analysis, the minimum reporting limits were 0.01 and 0.1 mg/L for TP and TN, respectively. Observations in the database below detection limits were replaced with values equal to one-half the detection limits since these observations were encountered infrequently (less than 15% of the total dataset). The method of using one-half the detection limit was reported to be sufficiently accurate for determining descriptive statistics like the mean and standard deviation (Dodds, 2006; Suplee et al., 2007; Hornung and Reed, 1990; US EPA, 2006).

1.3 Setting of reference conditions

The estimation of reference conditions is crucial in any ecological assessment program. These provide the baseline from which to determine lake change with time, and are necessary to evaluate a lake's current status or potential for change (Cardoso et al., 2007; Sa'nchez-Montoya et al., 2012). Reference conditions refer to the "naturalness" of the biota, in the absence of human disturbance or alteration and, as such, represent a target for remediation and restoration (Pardo et al., 2012). The reference lake approach is the most common method for establishing reference conditions at present (US EPA, 2000; Poikane et al., 2010; Huo et al., 2012; Cunha et al., 2011). Reference lakes are minimally impacted by human activity (e.g., with little or no riparian or watershed development) and therefore represent the "undisturbed" lakes within the region. A general rule of thumb for reference sample size should be at least 10% of the lake class of concern (US EPA, 2000). The 75th percentile of the frequency distribution of these reference lakes can be selected as the reference condition for each variable. Since there is a lack of information on reference lakes in the Eastern plain ecoregion, this approach is not an appropriate method for the ecoregion lakes. Therefore, the lake population distribution approach and trisection method can be used as surrogates (US EPA, 1998b, 2000; Pardo et al., 2012).

Though the lake population distribution approach does not involve the identification of reference lakes, it is possible to identify the reference values by the use of all the lake data presently available and selecting percentiles of frequency distribution for each variable in the ecoregion. The ecoregional reference condition should be acceptable and support all beneficial water uses. The 25th percentiles of TP, TN, and Chl-*a* reflecting high nutrient quality can be selected as the reference conditions for the ecoregion, because the 25th percentile will assure that the majority of the nutrient data from the entire regional lake population will not exceed the reference thresholds. Using the same logic described for SD, the opposite end of the distribution (i.e., upper 25th percentile) is used because greater SD is associated with higher water quality. In general, the 25th percentile of the frequency distribution of all lakes may be insufficient for lake protection if water quality has been severely degraded for most lakes in the ecoregion. Therefore, some lower percentile may be required as the reference condition of the lake ecoregion. If almost all reference lakes are impacted by human activity to some extent, the 5th percentile is recommended (US EPA, 2000).

Due to the heavy anthropogenic disturbances and pollution in the Eastern plain ecoregion, a lower percentile would be more appropriate for setting reference conditions than the 25th percentile, which would result in a relatively high proportion of lakes that would be assessed to have high status.

The trisection method is also a good alternative for determining reference conditions in the lake ecoregion. Some researchers more recently have adopted the trisection method recommended for biotic integrity indices (US EPA, 1998c) as a better alternative to this approach. The trisection method initially considered all the sampled lakes but retained only that third with the lowest nutrient or Chl-*a* concentrations or with the greatest SD, assuming that the least-impacted water bodies were represented by the best one-third of the distribution (US EPA, 1998b). Using the trisection method, median values derived from the best one-third of the data are considered indicative of the reference condition. The problem with this approach is its sensitivity to the proportion of impacted sites and the degree of regional impact (Dodds et al., 2006).

The final method for determining reference conditions predicted Chl-*a* and SD using multiple linear regressions. The predictors (independent variables) were selected from a number of chemical and physical constituents, including TP, TN, ammonia nitrogen (NH_3-N), pH, dissolved oxygen (DO), electric conductivity (EC), permanganate index (COD_{Mn}) and biochemical oxygen demand (BOD_5). Then reference values of the predictors were used to predict Chl-*a* and SD reference conditions.

It is well known that no single value can represent reference conditions over all types of water bodies. Lake ecosystems are complex and their characteristics mutually vary within large ranges, determined by external and internal factors (Moss et al., 2003). Therefore, the final results of reference conditions were expressed as ranges, not fixed values.

1.4 Statistical analysis

All data were transformed to their logarithms (base 10) before any statistical analyses to accommodate heterogeneity of variance. To derive reference conditions, descriptive statistics were used for TP, TN, Chl-*a* and SD (medians, quartiles and percentiles). Relationships between the aforementioned variables were initially described by Pearson correlations and inspection of scatter plots. Linear regression models via the stepwise method were used for predicting Chl-*a* value and SD.

2 Results and discussion

2.1 Reference conditions established by population distribution and trisection methods

Lakes that are known to be severely impaired may be excluded from the sample, if desired. The population distribution of each selected variable is determined, and the best quartile or lower 5th to 25th percentile of the distribution of each nutrient variable is taken as its reference value for shallow lakes in the Eastern plain ecoregion. Reference conditions for TP, TN, Chl-*a* and SD based on the dataset of all lakes can be seen in **Table 1**.

Reference values determined for the best one-third of lakes (trisection method) were nearly bracketed by values derived from the method of lake population distribution, suggesting that the trisection method lends itself to more conservative estimates of reference conditions. Median reference Chl-*a* values were 3.92 mg/m^3 for the trisection method and 1.78–4.73 mg/m^3 for the method of lake population distribution (**Table 1**). Reference SD values were 0.86 m for the trisection method and 0.68–1.21 m for the method of lake population distribution (**Table 1**). Reference TP values had a median of 0.029 mg/L for the trisection method and 0.014–0.043 mg/L for the method of lake population distribution (**Table 1**). Finally, reference TN concentrations had a median value of 0.67 mg/L for the trisection method and 0.360–0.785 mg/L for the method of lake population distribution (**Table 1**).

2.2 Multiple regression models for reference Chl-*a* and SD

Prior to model development, Pearson correlations were computed for each pair of variables to select the potential predictor variables (**Table 2**). In the Eastern plain ecoregion, there were significant correlations between nutrients and other variables; Chl-*a* and SD were both correlated with organic matter as well as nutrients (**Table 2** and **Fig. 1**).

Significant positive correlations between the causal variables TP, TN, NH_3-N, COD_{Mn} and response variable Chl-*a* were found, which indicate that phosphorus and nitrogen are essential nutrients necessary for the growth of phytoplankton in Eastern plain ecoregion lakes in China.

Table 1 TP, TN, Chl-*a* concentrations and SD in east plain ecoregion lakes

Variables	5%	25%	Median	75%	95%	*n*
TP (mg/L)	0.014	0.043	0.088	0.150	0.266	454
TN (mg/L)	0.360	0.785	1.245	2.074	3.781	416
Chl-*a* (mg/m^3)	1.78	4.73	8.69	15.09	26.99	162
SD (m)	1.21	0.68	0.50	0.41	0.28	172

TP: total phosphorus; TN: total nitrogen. SD: opposite end of the distribution.

Table 2 Correlations between enrichment measures and physical variables in Eastern plain ecoregion lakes

	Chl-*a*	SD	TP	TN	NH_3-N	pH	EC	DO	COD_{Mn}	BOD_5
Chl-*a*	1									
SD	–0.419**	1								
TP	0.423**	–0.659**	1							
TN	0.293**	–0.394**	0.666**	1						
NH_3-N	0.327**	–0.407**	0.657**	0.718**	1					
pH	0.197*	–0.205**	0.086	0.078	–0.082	1				
EC	0.201	–0.261*	0.513**	0.489**	0.373**	0.396**	1			
DO	0.046	–0.063	–0.247**	–0.291**	–0.270**	0.177**	–0.167**	1		
COD_{Mn}	0.399**	–0.660**	0.702**	0.558**	0.625**	0.122*	0.644**	–0.178**	1	
BOD_5	0.613**	–0.171*	0.472**	0.511**	0.643**	0.040	0.365**	–0.197**	0.623**	1

*Correlation is significant at the 0.05 level (2-tailed); **correlation is significant at the 0.01 level (2-tailed). EC: electric conductivity; COD_{Mn}: permanganate index; BOD_5: biochemical oxygen demand.

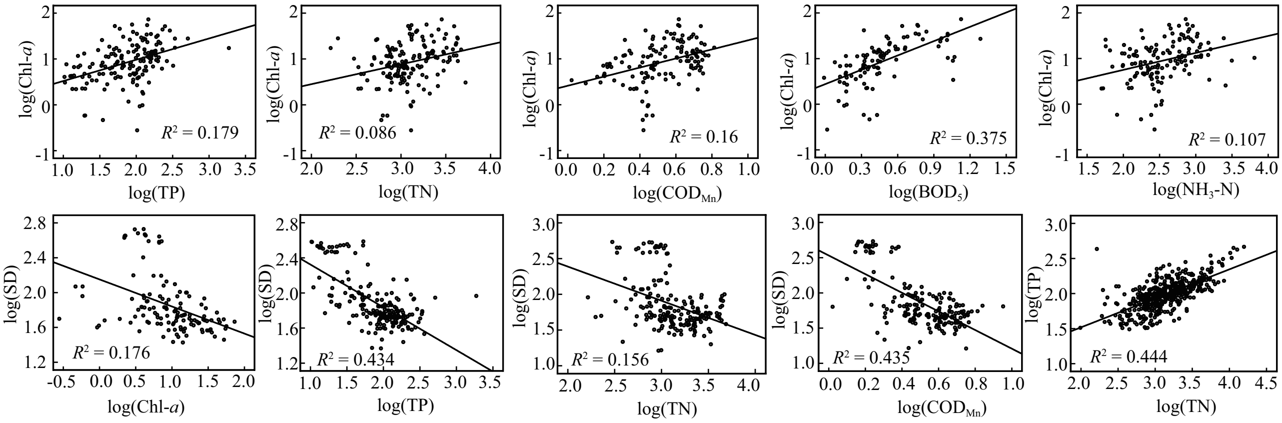

Fig. 1 Relationships between some variables for Eastern plain ecoregion lakes.

Furthermore, phosphorus can be considered to be the nutrient that regulates the production of algae and is most amenable to control in this ecoregion's lakes. A poor negative correlation between Chl-*a* and SD was also found, which indicated that non-algal particles influenced the SD.

Multiple linear regression models were built to predict Chl-*a* and SD using all the available lake data from the database (**Table 3**). Variables were listed in the order in which they explained model variance, and the *p* values were less than 0.0001 for each model. Then reference values were used for the independent variables to predict the Chl-*a* and SD associated with those concentrations. The predicted values from the linear regression were very close to the values derived directly from the statistical distribution. These models should be validated with future reference lake data, but the modeling approach holds promise as a potential tool for predicting Chl-*a* reference targets and certainly supports the reference targets derived directly from the statistical distribution of Chl-*a* and SD.

2.3 Reference conditions in eastern plain ecoregion lakes

In view of statistical methods from collected data, the results were liable to be influenced by the sample size. Therefore, it is better to use historical information, paleolimnological analysis and modeling tools as support and validation (US EPA, 2000; Dodds et al., 2006).

In the Eastern plain ecoregion, the 5th percentile of the distribution for typical lakes severely impaired by human disturbance was considered as high quality status (**Table 4**). For TP, TN and SD the values were 0.022–0.052 mg/L, 0.33–0.79 mg/L, and 0.50–1.10 m, respectively, almost the same as the reference conditions set previously, and Chl-*a* concentrations were slightly lower.

Historical data probably give the best insight into how reference conditions looked. The "reference period" is usually considered the period before the Second World War if impacts from anthropogenic land use and urbanization can be considered as negligible (Poikane et al., 2010). The

Table 3 Multiple linear regression models to predict Chl-*a* and SD from lake chemistry. (unit of TP and TN: μg/L)

Models	R^2	Predicted values
log(Chl-*a*) = –0.135+0.368log(TP)+0.103log(TN)	0.164	3.90
log(Chl-*a*) = –0.467+0.734log(BOD_5)+0.516log(TP)	0.432	2.53
log(Chl-*a*) = –0.915+0.731log(BOD_5)+0.350log(TP)+ 0.244log(TN)	0.441	1.44
log(SD) = 2.152–0.311log(Chl-*a*)	0.176	0.93

Table 4 High quality status (5th percentile) for TP, TN, Chl-*a*, SD in East plain ecoregion lakes

	TP (mg/L)	TN (mg/L)	Chl-*a* (mg/m^3)	SD (m)
Chaohu Lake	0.029	0.63	0.67	0.64
Dianshan Lake	0.052	0.79	2.33	0.90
East Lake	0.031	0.55	–	–
Dongting Lake	0.022	0.69	0.24	0.90
Hongze Lake	0.046	0.56	2.40	–
Poyang Lake	0.030	0.33	1.00	1.10
Taihu Lake	0.026	0.77	2.00	0.50

"–": no data.

results of paleolimnological reconstruction of past conditions showed that the baseline TP concentration was about 0.050 mg/L for many lakes in the Eastern plain ecoregion (Dong et al., 2006, 2008; Yang et al., 2008). Some research suggested that reference conditions established through watershed models were consistent with those of other approaches. For example, the reference values for Chaohu Lake (in the Eastern plain ecoregion) identified by the modeling approach based on system dynamics were TP of 0.034–0.039 mg/L, TN of 0.41–0.66 mg/L, Chl-*a* of 5.9–6.8 mg/m^3, and SD of about 1 m (Zhang et al., 2011), quite close to the values in this article.

In summary, the values and ranges considered as nutrient reference conditions for lakes in the Eastern plain ecoregion are given as follows: TP concentration is 0.029 mg/L or 0.014–0.043 mg/L, TN is 0.67 mg/L or 0.360–0.785 mg/L, Chl-*a* is 3.92 mg/m^3 or 1.78–4.73 mg/m^3, SD is 0.85 m or 0.68–1.21 m.

3 Conclusions

Determining reference conditions in lakes is an important tool for environmental management, and will help set protection goals and guide regulation and restoration of water bodies. In this study, nutrient reference conditions for lakes in the Eastern plain ecoregion were established by the lake population distribution approach and the trisection method. The reference condition value for lakes in Eastern plain ecoregion by the trisection method is TP of 0.029 mg/L, TN of 0.67 mg/L, Chl-*a* of 3.92 mg/m^3, SD of 0.85 m and the reference condition range by the lake population distribution approach is TP of 0.014–0.043 mg/L, TN of 0.360–0.785 mg/L, Chl-*a* of 1.78–4.73 mg/m^3, SD of 0.68–1.21 m. Additionally, empirical models were developed for estimating reference Chl-*a* concentration and SD successfully for lakes in Eastern plain ecoregion. The results of different approaches for setting reference conditions by using at least three potential available approaches may make the reference values more credible and defensible. Any one approach may yield an unexpectedly high or low reference value, but such a value can be checked by the other approaches. The final values of reference conditions were checked by information from the historical record as well as paleolimnological and model research.

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