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Using Fuzzy Theory and Variable Weights for Water Quality Evaluation in Poyang Lake, China

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Abstract: Achieving water purity in Poyang Lake has become a major concern in recent years, thus appropriate evaluation of spatial and temporal water quality variations has become essential. Variations in 11 water quality parameters from 15 sampling sites in Poyang Lake were investigated from 2009 to 2012. An integrative fuzzy variable evaluation (IFVE) model based on fuzzy theory and variable weights was developed to measure variations in water quality. Results showed that: 1) only chlorophyll-a concentration and Secchi depth differed significantly among the 15 sampling sites ($P < 0.01$), whereas the 11 water quality parameters under investigation differed significantly throughout the seasons ($P < 0.01$). The annual variations of all water quality variables except for temperature, electrical conductivity, suspended solids and total phosphorus were considerable ($P < 0.05$). 2) The IFVE model was reasonable and flexible in evaluating water quality status and any possible 'bucket effect'. The model fully considered the influences of extremely poor indices on overall water quality. 3) A spatial analysis indicated that anthropogenic activities (particularly industrial sewage and dredging) and lake bed topography might directly affect water quality in Poyang Lake. Meanwhile, hydrological status and sewage discharged into the lake might be responsible for seasonal water quality variations.
Keywords: fuzzy theory; bucket effect; variable weights; water quality; Poyang Lake

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1 Introduction

Attaining and maintaining good water quality has long been an urgent objective of water resource managers and government decision makers (Zhang and Dong, 2009; Norman *et al*., 2013). This objective frequently poses a challenge to environmental engineers and hydrologists because of the complexities and uncertainties of evaluation processes (Dahiya *et al*., 2007; Wong and Hu, 2014). However, unregulated anthropogenic activities, coupled with intensifying global climate change, have caused various water pollution problems (Debels *et al*., 2005; Qadir *et al*., 2008; Vörösmarty *et al*., 2010). Thus, effective water quality evaluation methods that consider both complexity and uncertainty must be established to formulate concrete guidelines from standardized indices on the current and changing status of lake water.

Many scholars have demonstrated interests in water quality evaluation research (Alberto *et al*., 2001; Chang *et al*., 2001; Shrestha and Kazama, 2007; Palma *et al*., 2010; Beyhan and Kaçıkoç, 2014). These scholars have developed numerous evaluation methods or models, such as multivariable statistical methods (e.g., principle component analysis, factor analysis, cluster analysis, and discriminant analysis) (Simeonov *et al*., 2003;

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Ouyang *et al*., 2006; Palma *et al*., 2010; Li *et al*., 2015), the composite water quality identification index (CWQII) (Qun *et al*., 2009; Ban *et al*., 2014), the poorest index selection method (Chinese Environmental Protection Agency (CEPA), 2002), the probabilistic index (Beamonte *et al*., 2005; Cordoba *et al*., 2010), and the integrative pollution index (Liu *et al*. 2011). However, more efficient water quality evaluation index systems and integrative methods still need to be explored, particularly for lakes, for which only eutrophication has been focused on in past research (Beyhan and Kaçıkoç, 2014). Fuzzy set theory, rough set theory and grey system theory are effective methods that help ecologists handle the complexities and uncertainties of evaluating water quality (Karmakar and Mujumdar, 2006; Dahiya *et al*., 2007; Ip *et al*., 2007). In particular, fuzzy theory is widely used because of its advantages in solving problems with fuzzy boundaries and controlling the effect of sampling errors on evaluation results (Ocampo-Duque *et al*., 2006; Liu *et al*., 2010). Furthermore, the information entropy method is believed to contain most of the information about elements and the relationships among assessed objects (Zou *et al*., 2006; Liu *et al*., 2010). However, constant weights do not represent dynamic changes in variable importance. For example, the ′bucket effect′, wherein the evaluation results become poor after a certain index exceeds its water quality threshold, must be considered in the process of water quality evaluation. Thus, variable weights, which vary depending on the situation, should be explored to evaluate the dynamic properties of water quality. Such evaluation will also help assess the influence of the bucket effect on a water quality index system.

The World Wide Fund for Nature lists Poyang Lake as a globally important eco-region because its unique ecological environment reflects the economic development of humans and society. This region also provides a habitat for rare migratory birds in winter. Moreover, Poyang Lake partly determines the status of the water environment in the lower reaches of the Yangtze River. With regard to water quality evaluation, Yan *et al*. (2012) focused on the impact of land-use change on the states of water quality in Poyang Lake basin. Wu *et al*. (2011) discovered that the water quality of Poyang Lake underwent considerable changes after 2003 because of the impounding of the Three Gorges Dam. However, the present evaluation of water quality is confined within the Chinese surface water quality standards (GB-2002) using the poorest index method, which identifies water quality via the worst index while merely considering the integrative and bucket effect of indices. Moreover, the state of water quality is influenced by several factors including precipitation, discharge, flow velocity, and pollutant emission, which may differ among estuaries, lakes, and stream channels to the Yangtze River. Furthermore, water quality varies across seasons and years. Therefore, establishing a proper method to evaluate spatial and temporal variations in the water quality of Poyang Lake is essential.

In this study, an integrative fuzzy variable evaluation (IFVE) model was established to evaluate temporal and spatial water quality variations in Poyang Lake from 2009 to 2012. The following steps were taken: 1) a total of 11 water quality parameters were obtained seasonally in 15 sites from 2009 to 2012. 2) The inter- and intra-annual variations of the 11 water quality parameters in the chosen sites were analyzed. 3) The conceptual framework of the IFVE model was introduced and improvements from information entropy weights to variable weights were proposed. 4) Five representative water quality parameters were selected, and the model was applied to investigate temporal and spatial variations of water quality in Poyang Lake. This study will provide an efficient water quality evaluation method and aid in future water management decisions for maintaining water quality.

2 Materials and Methods

2.1 Study area

Poyang Lake (28°22′–29°45′N, 115°47′–116°45′E) is located on the southern bank of the Yangtze River of China (Fig. 1). It is fed primarily from five tributaries (Ganjiang River, Fuhe River, Xinjiang River, Raohe River, and Xiushui River) and is freely connected to the Yangtze River at the outlet of lake (Hukou). This area is characterized as a subtropical monsoon climate. The annual average temperature is 17.6℃, and the mean annual precipitation ranges from 1450 to 1550 mm, which mostly occurs in summer. As the streamflow varies by seasons, the surface area of Poyang Lake can fluctuate significantly from less than 1000 km^2 in the dry season (Fig. 1c) to approximately 4000 km^2 in the flood season (Fig. 1b) (Shankman *et al*., 2006), when the lake can be described as 'flooding like sea, and drying like thread'. As the largest freshwater lake in China, Poyang Lake nourishes a drainage area of 1.622 × 10^5 km^2, which plays a significant role in supplying freshwater and fish, restricting floods, regulating the climate, and degrading pollutants. However, intensive anthropogenic activities have adversely affected the water quality of Poyang Lake. Previous studies have indicated that non-point source pollution from domestic sewage, and runoff pollution from agricultural and residential areas are the primary sources of pollution in Poyang Lake (Yan *et al*., 2011). Water quality in the lake has undergone considerable changes since 2003 and is showing a tendency toward deterioration (Wu *et al*., 2011). Algal blooms have even been detected in several areas of Poyang Lake (Xu *et al*. 2012). Water management in Poyang Lake will certainly face greater challenges in the future under the dual influence of operation of the Three Gorges Dam and global climate changes.

2.2 Data

Figure 1 shows the distribution of the sampling sites throughout Poyang Lake and its tributaries. Water samples were taken from 15 sampling sites every 3 months from Jan. 2009 to Oct. 2012. Considering pollution features in Poyang Lake and water quality index in China, 11 water quality parameters including pH, chlorophyll-a (Chl-a), temperature (T), Secchi depth (SD), electrical conductivity (EC), suspended solids (SS), dissolved oxygen (DO), chemical oxygen demand (COD_{Mn}), total nitrogen concentration (TN), total phosphorus concentration (TP), and ammonia nitrogen (NH_4^+–N) were selected to analyze water quality in Poyang Lake. These sites were selected based on the size of the lake and its proximity to rivers and human activities. For example, Site 1 was adjacent to the outlet of the Raohe River. Site 11 was located at the junction of the lake and the Yangtze River; Site 8 was located at the outlet of a subsidiary lake called Bang Lake, and Site 13 was dominated by chemical industries and sand trading centers. In addition, all the sampling sites were covered by water throughout the entire year, despite the seasonal variation in the water levels of Poyang Lake (Fig. 1). Analysis of variance (ANOVA) based on SPSS 20.0 was used to analyze variations in the characteristics of 11 water parameters at all the sites (across all seasons) and among seasons (across all the sites). Among them, 5 widely used parameters namely, DO, TN, TP, COD_{Mn}, and NH_4^+–N were used for the water quality evaluation (Ban *et al*., 2014), on the basis of the IFVE model. July 2010, October 2010, January 2011, and April 2011 were excluded from the evaluation process because of missing NH_4^+–N data.

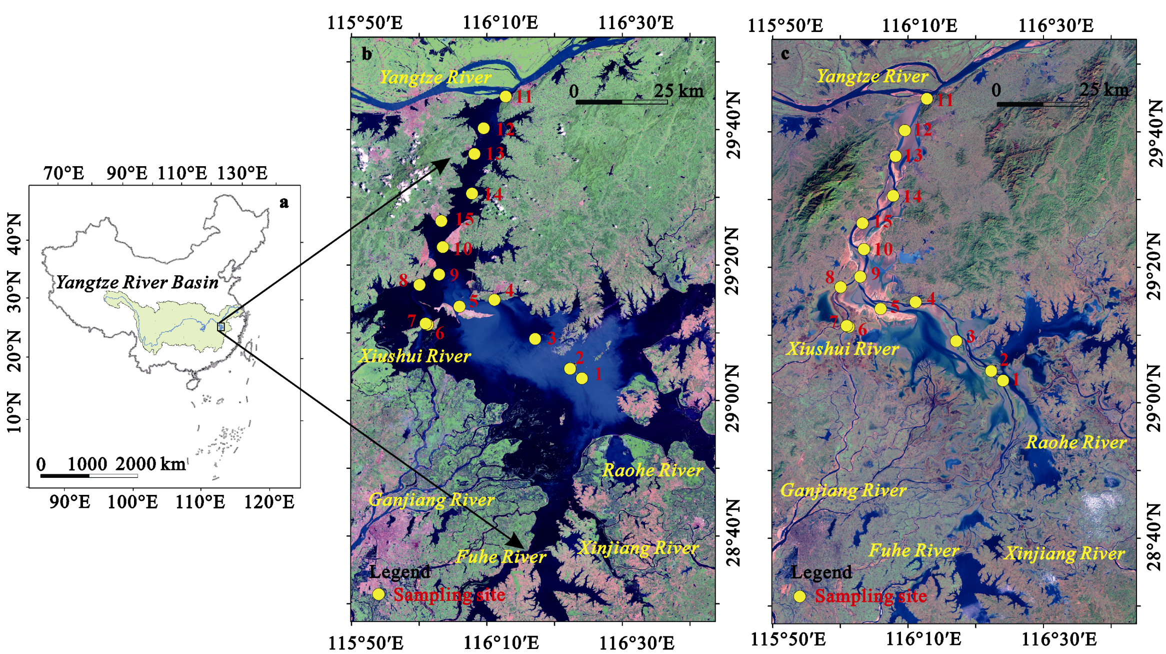

Fig. 1 Seasonal variation in Poyang Lake, China (a) and locations of sampling sites: (b: summer; c: winter)

2.3 Conceptual framework of IFVE model

Fuzzy theory, which was introduced by Zadeh (1965), is defined in terms of membership function. It has been widely applied in evaluating vague and complicated processes (Dahiya *et al*., 2007). In this study, we combine fuzzy theory with variable weights based on information entropy to establish the IFVE model in four steps: 1) acquire the membership matrix based on water quality parameters and standards; 2) calculate the constant weights using the information entropy method; 3) determine variable weights based on constant weights; and 4) perform the IFVE. The next section describes the steps in detail.

2.3.1 Establishing membership functions

In fuzzy theory, membership degree measures the extent to which a specific value is associated with a certain water quality classification. Based on the national surface water environmental quality standards of China (CEPA, 2002), the water quality is classified into five classifications (I, II, III, IV, V) (Table 1). Then five representative water quality parameters were identified either as benefit (i.e., the larger, the better) or cost ones (i.e., the smaller, the better). The membership functions for cost indices are provided as follows:

$$r_{i1}(x_{ij})=\begin{cases}1 & x_{ij}\in(0,s_{i1}]\\(s_{i2}-x_{ij})/(s_{i2}-s_{i1}) & x_{ij}\in(s_{i1},s_{i2}]\\0 & x_{ij}\in(s_{i2},+\infty)\end{cases}\tag{1}$$

$$r_{ik}(x_{ij})=\begin{cases}0 & x_{ij}\in(0,s_{i(k-1)}]\\(x_{ij}-s_{i(k-1)})/(s_{ik}-s_{i(k-1)}) & x_{ij}\in(s_{i(k-1)},s_{ik}]\\(s_{i(k+1)}-x_{ij})/(s_{i(k+1)}-s_{ik}) & x_{ij}\in(s_{ik},s_{i(k+1)}]\\0 & x_{ij}\in(s_{i(k+1)},+\infty)\end{cases}\tag{2}$$

$$r_{ic}(x_{ij})=\begin{cases}0 & x_{ij}\in(0,s_{i(c-1)}]\\(x_{ij}-s_{i(c-1)})/(s_{ic}-s_{i(c-1)}) & x_{ij}\in(s_{i(c-1)},s_{ic}]\\1 & x_{ij}\in(s_{ic},+\infty)\end{cases}\tag{3}$$

where $r_{i1}(x_{ij})$ is the membership degree of the *i*th indicator from the *j*th water sample to the first class (I). Similarly, r_{ik} is the membership degree of the *i*th indicator from the *j*th object to the *k*th class, and *k* satisfies $1 < k < c$, where *c* is the highest class ($c = 5$ in this study). x_{ij} is the measured value of the *j*th object for the *i*th indicator. s_{ik} is the standard value from the water quality criteria from the *i*th indicator for the *k*th class (Table 1).

Table 1 Water quality classes based on the Environmental Quality Standard for Surface Water, China (GB3838–2002) (mg/L)

Parameter	Class of water quality				
	I	II	III	IV	V
DO (≥)	7.5	6.0	5.0	3.0	2.0
COD_{Mn} (≤)	2.0	4.0	6.0	10.0	15.0
TN (≤)	0.2	0.5	1.0	1.5	2.0
TP (≤)	0.010	0.025	0.050	0.100	0.200
NH_4^+–N (≤)	0.15	0.50	1.00	1.50	2.00

Notes: DO: dissolved oxygen; COD_{Mn}: chemical oxygen demand; TN: total nitrogen concentration; TP: total phosphorus concentration; NH_4^+–N: ammonia nitrogen

2.3.2 Assigning variable weight matrices

The information entropy method is widely utilized to assign weights because of its efficient use of available data. Moreover, it is regarded to be objective because of its exclusion of human factors (Liang and Shi, 2004). The constant weights base on the entropy method was calculated at various scales (seasonally, annually, spatially, and in totality) according to Zou *et al*. (2006).

Variable weights, which were introduced by Wang (1983) and developed by Li *et al*. (2004), were used to alleviate the possible neutralization of strong and weak indices (Li *et al*., 2010). The formula for variable weights is given as follows:

$$w_{ij}(x)=cw_iS_{ij}(x)/\sum_{i=1}^{m}cw_iS_{ij}(x)\tag{4}$$

$$S_{ij}(x)=\begin{cases}1 & x_{ij}\in[0,a_i)\\2-\log a_i(x_{ij}+\lambda) & x_{ij}\in[a_i,+\infty)\end{cases}\tag{5}$$

where w_{ij} is the variable weight of the *i*th parameter for *j*th water sample, whereas cw_i is the constant weight of the *i*th parameter calculated using the entropy method, and $S_{ij}(x)$ is the variable weight state vector of the *i*th parameter for *j*th water sample. a_i represents the breaking point of the *i*th parameter, the value of which is s_{i5}. When the parameter exceeds a_i, the variable weights are triggered to punish this parameter. When no parameter exceeds the threshold, the weights are identical to the constant weights. λ is a parameter close to zero to make the model meaningful when x_{ij} is zero. Furthermore it indicates punishment strength; that is, a smaller λ leads to a harsher punishment, which shows that the bucket effect is stronger (Shu *et al*., 2012). In this study, we propose that $\lambda = 0.01$. Furthermore, the integrative fuzzy evaluation (IFE) model based on constant weights is also applied for comparison with the IFVE model (Zou *et al*., 2006).

2.3.3 Non-integral assessment grade computation

The membership degree matrices for the evaluation of objects in five water quality classes, namely, 'I' to 'V', were obtained by combining variable weights and fuzzy membership degree matrices (Formula (6)). Then, they were plotted to qualitatively evaluate water quality. In addition, considering the inadaptability of the maximum membership principle, the water quality grades were determined via a non-integral rank feature value (H_i) obtained using Formula (7) and were classified into 'good', 'medium', 'poor', and 'bad' (Table 2).

$$B_j = W \times R = (b_{j1}, \ldots, b_{jk}, \ldots, b_{jc}) \tag{6}$$

where b_{jk} represents the membership degree of the jth water sample to the kth water quality class, and $W = (w_{ij})_{n\times m}$, fuzzy matrix $R = (r_{ij})_{m\times n}$.

$$H_j = \sum_{k=1}^{c} k \times b_{jk} \tag{7}$$

where H_j is the non-integral rank feature value for the jth water sample.

3 Results and Analyses

3.1 Variations in water quality variables

No remarkable spatial variation was detected in the 15 sampling sites, except for Chl-a and SD ($P < 0.01$) (Table 3). The average concentration of Chl-a varied from 2.90 to 10.6 μg/L, with the highest value of Site 8. Similarly, SD was significantly high in Site 7 (0.56 m), which was located at the outlet of the Xiushui River. Moreover, the concentration of COD_{Mn} was also remarkably higher in Site 8 compared with those in Sites 6 and 7 ($P < 0.05$). Furthermore, TN and TP also exhibited variations ($P = 0.07$ and $P = 0.11$, respectively), with Site 1 having the highest values at 2.2 mg/L and 0.16 mg/L, respectively. The spatial variation of water quality parameters in Poyang Lake is site-specific. Significant seasonal variations were found for all the 11 parameters in Poyang Lake ($P < 0.01$) (Table 4). Among these, the mean concentration of Chl-a was found to be 5.19 μg/L, with a maximum of 6.44 μg/L in summer and a minimum of 3.13 μg/L in winter. Meanwhile, DO concentration presented a reverse trend, with a maximum of 11.53 mg/L in winter and a minimum of 6.46 mg/L in summer. This trend could be attributed to the dependence of DO solubility on T, which was warmest at 30.13℃ in summer and coolest at 6.38℃ in winter. Similarly, EC, SS, TN, TP and NH_4^+–N were also at their highest values in winter (202.16 μs/cm, 75.81 mg/L, 2.23 mg/L, 0.13 mg/L, and 0.7 mg/L, respectively) and lowest in summer (103.19 μs/cm, 28.29 mg/L, 1.14 mg/L, 0.05 mg/L, and 0.1 mg/L, respectively). Annual variations in water quality variables, with the exception of T, EC, SS, and TP, were significant ($P < 0.05$). Highest Chl-a (6.56 μg/L), EC (164.6 μs/cm), SS (73.98 mg/L), COD_{Mn} (3.5 mg/L) and TN (1.94 mg/L) and lowest DO level (7.55 mg/L) were found in 2011. The temporal variations, particularly the seasonal variations for most parameters were significant, which could be attributed to hydrological conditions and sewage effluent.

Table 2 Scale of water quality rank feature values

Scale (H_j)	1–2	2–3	3–4	4–5
Grade	Good	Medium	Poor	Bad

Note: H_j is the non-integral rank feature value for the jth water sample

3.2 Water quality evaluation for 15 sampling sites

Table 5 shows the non-integral rank feature value (H) for each sampling site and campaign based on the IFVE model. Overall, January and October obtained the worst water quality, whereas water quality in most sites in April and July could be classified as 'good' to 'medium', with indices barely exceeding their thresholds. Temporally, January 2010 had the worst water quality, with 10 sites classified as 'poor' and Sites 1 and 12 classified as 'bad'. Meanwhile, July 2009, April 2012 and July 2012 had relatively desirable water quality, ranging from 'good' to 'medium'. Spatially, 3 to 4 sampling months in Sites 1, 10 and 13, had 'poor' or 'bad' water quality. Notably, Site 7 presented the best water quality, as all of its sampling months were ranked 'good' or 'medium'.

Water quality was worst in winter and best in summer and better in spring than in autumn (Fig. 2). In winter, Site 1 was evaluated as 'bad'. Sites 4 and 11–14 were classified as 'poor' because the bucket effect demonstrated an overload of TN. The other nine sites were classified as 'medium'. However, no variable weight was detected in other seasons. For example, all the sampling sites were classified as 'medium' in spring, except for Sites 6 and 12, which were 'good'. In summer, Sites 3, 4,

Table 3 Mean values with standard deviation (in parentheses) of different water quality parameters in 15 sampling sites in Poyang Lake of China from 2009 to 2012

Samping site	pH	Chl-a (μg/L)	T (℃)	SD (m)	EC (μs/cm)	SS (mg/L)	DO (mg/L)	COD_{Mn} (mg/L)	TN (mg/L)	TP (mg/L)	NH_4^+–N (mg/L)
1	7.72	4.52	20.11	0.51	148.96	50.62	8.46	2.97	2.20	0.16	0.63
	(0.44)	(2.73)	(9.26)	(0.30)	(81.71)	(48.51)	(2.39)	(0.97)	(1.21)	(0.14)	(0.76)
2	7.75	4.92	20.82	0.53	106.99	31.93	8.33	2.92	1.41	0.09	0.25
	(0.44)	(4.15)	(9.45)	(0.24)	(33.40)	(18.43)	(2.96)	(0.91)	(0.40)	(0.08)	(0.17)
3	7.87	6.88	19.61	0.50	122.09	41.22	8.65	2.69	1.41	0.10	0.27
	(0.38)	(5.25)	(9.92)	(0.24)	(41.29)	(36.81)	(2.62)	(0.74)	(0.41)	(0.08)	(0.15)
4	8.01	6.76	19.98	0.46	133.73	54.65	9.09	2.92	1.66	0.13	0.46
	(0.49)	(4.4)	(10.31)	(0.29)	(46.11)	(48.42)	(3.03)	(0.91)	(0.67)	(0.10)	(0.37)
5	7.90	6.25	19.53	0.33	137.61	67.17	8.33	2.90	1.60	0.11	0.45
	(0.49)	(4.83)	(9.92)	(0.17)	(44.17)	(61.79)	(2.37)	(1.02)	(0.52)	(0.07)	(0.54)
6	7.90	5.93	19.49	0.47	134.96	44.22	8.21	2.47	1.57	0.06	0.32
	(0.60)	(5.15)	(8.85)	(0.25)	(47.65)	(32.17)	(1.95)	(0.56)	(0.58)	(0.02)	(0.29)
7	8.09	6.26	19.99	0.56	130.97	28.45	9.52	2.46	1.39	0.06	0.30
	(0.55)	(5.03)	(8.98)	(0.25)	39.67	(19.86)	(3.29)	(0.79)	(0.63)	(0.03)	(0.32)
8	8.05	10.64	18.32	0.43	220.08	34.61	8.52	3.87	1.39	0.08	0.30
	(0.51)	(8.04)	(10.02)	(0.20)	(158.98)	(24.70)	(2.36)	(2.66)	(0.57)	(0.06)	(0.46)
9	7.84	4.81	18.72	0.38	172.73	70.01	8.27	2.99	1.62	0.09	0.30
	(0.47)	(4.01)	(9.98)	(0.12)	(165.37)	(115.55)	(2.24)	(0.85)	(0.47)	(0.05)	(0.27)
10	7.87	4.35	19.01	0.27	140.63	93.05	8.28	2.79	1.72	0.13	0.30
	(0.38)	(2.77)	(9.50)	(0.12)	(42.95)	(84.47)	(2.32)	(0.73)	(0.56)	(0.18)	(0.27)
11	7.84	2.98	19.08	0.28	158.08	73.72	8.50	3.06	1.81	0.09	0.27
	(0.51)	(1.41)	(8.97)	(0.16)	(65.42)	(56.38)	(2.78)	(1.02)	(0.74)	(0.06)	(0.23)
12	7.82	2.90	19.30	0.28	144.09	66.12	8.29	2.90	1.70	0.10	0.58
	(0.46)	(1.33)	(9.17)	(0.14)	(41.44)	(49.12)	(2.45)	(1.02)	(0.69)	(0.06)	(1.16)
13	7.79	3.50	19.31	0.25	145.64	70.15	8.42	2.90	1.74	0.09	0.53
	(0.47)	(1.78)	(9.14)	(0.12)	(40.92)	(65.58)	(2.71)	(1.29)	(0.65)	(0.06)	(0.95)
14	7.82	2.92	19.41	0.25	140.96	68.59	8.10	2.87	1.73	0.09	0.29
	(0.49)	(1.10)	(9.15)	(0.13)	(42.15)	(50.36)	(2.22)	(1.06)	(0.67)	(0.05)	(0.20)
15	7.88	4.40	19.68	0.31	141.18	59.18	8.22	2.80	1.75	0.08	0.29
	(0.41)	(3.33)	(9.32)	(0.15)	(42.66)	(48.14)	(2.27)	(0.98)	(0.64)	(0.05)	(0.21)
P	0.436	<0.010	1.000	<0.010	0.245	0.763	0.988	0.227	0.075	0.112	0.758

Notes: T: temperature; SD: Secchi depth; EC: electrical conductivity; SS: suspended solids. Other abbreviations see Table 1

Table 4 Mean values with standard deviation (in parentheses) of different water quality variables at different seasons and years in Poyang Lake during 2009–2012

	pH	Chl-a (μg/L)	T (℃)	SD (m)	EC (μs/cm)	SS (mg/L)	DO (mg/L)	COD_{Mn} (mg/L)	TN (mg/L)	TP (mg/L)	NH_4^+–N (mg/L)
Winter	7.95	3.13	6.38	0.27	202.16	75.81	11.53	3.40	2.23	0.13	0.70
	(0.26)	(3.36)	(1.17)	(0.14)	(96.51)	(57.60)	(1.14)	(1.82)	(0.74)	(0.08)	(0.71)
Spring	8.03	4.88	16.84	0.41	144.09	55.58	8.24	2.97	1.68	0.09	0.35
	(0.65)	(4.35)	(3.02)	(0.22)	(79.17)	(49.19)	(1.34)	(0.75)	(0.53)	(0.11)	(0.52)
Summer	7.74	6.44	30.13	0.50	103.19	28.92	6.46	2.70	1.14	0.05	0.10
	(0.51)	(4.35)	(1.07)	(0.25)	(41.61)	(34.38)	(1.03)	(0.78)	(0.35)	(0.02)	(0.05)
Autumn	7.79	6.32	24.37	0.38	133.13	72.51	7.49	2.52	1.54	0.12	0.33
	(0.32)	(4.91)	(3.71)	(0.22)	(36.48)	(70.65)	(2.08)	(0.60)	(0.51)	(0.08)	(0.33)
P	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
2009	7.74	3.99	21.86	0.52	126.90	49.08	8.92	2.84	1.48	0.10	0.23
	(0.35)	(2.85)	(9.99)	(0.21)	(33.64)	(65.46)	(2.41)	(1.53)	(0.56)	(0.10)	(0.21)
2010	7.59	5.11	18.1	0.37	140.98	49.46	8.21	2.36	1.49	0.08	–
	(0.46)	(5.67)	(8.99)	(0.19)	(109.60)	(45.37)	(2.75)	(0.67)	(0.64)	(0.08)	–
2011	7.81	6.56	18.14	0.35	164.60	73.98	7.55	3.50	1.94	0.10	–
	(0.17)	(4.77)	(9.15)	(0.24)	(78.99)	(61.80)	(1.67)	(0.94)	(0.60)	(0.06)	–
2012	8.37	5.13	19.87	0.34	148.8	54.58	9.25	2.90	1.68	0.11	0.33
	(0.44)	(3.74)	(8.44)	(0.21)	(59.67)	(48.91)	(2.76)	(0.98)	(0.78)	(0.09)	(0.36)
P	<0.01	0.02	0.08	<0.01	0.06	0.06	<0.01	<0.01	<0.01	0.47	–

Table 5 Non-integral rank feature value based on the IFVE model

Date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2009-01	3.48	2.09	2.12	2.13	2.52	2.29	1.97	3.02	2.23	2.26	2.27	2.30	2.04	2.26	2.13
2009-04	1.76	1.73	2.18	2.36	1.69	2.30	1.76	1.79	1.76	3.68	1.57	1.67	1.60	1.65	1.77
2009-07	1.96	1.90	1.78	1.85	1.62	2.04	1.79	1.81	2.17	1.94	1.85	2.11	2.09	2.10	1.86
2009-10	2.51	2.40	2.48	2.27	2.35	2.76	1.77	2.10	3.11	3.25	3.51	3.65	3.69	3.93	3.46
2010-01	4.78	2.80	2.34	3.59	3.58	3.24	2.57	3.88	3.08	3.50	3.71	4.19	3.40	3.46	3.36
2010-04	2.40	2.75	2.66	2.74	2.40	3.33	1.92	1.99	2.56	2.37	2.23	1.96	3.42	2.30	2.26
2011-07	2.37	2.20	2.58	1.77	2.35	2.10	2.42	2.09	2.46	2.32	2.13	2.20	2.15	2.37	2.19
2011-10	2.26	2.25	2.53	2.93	3.14	2.12	2.54	2.40	2.76	2.64	2.79	2.87	2.84	2.53	2.70
2012-01	4.22	1.92	2.18	2.80	2.73	2.47	1.70	1.79	2.18	2.48	2.80	2.65	2.70	2.73	2.61
2012-04	2.39	2.25	2.10	2.54	2.42	1.94	2.30	2.21	2.43	2.76	2.53	2.04	2.51	2.42	2.57
2012-07	2.00	1.90	1.29	1.85	1.86	2.03	1.80	1.80	1.81	1.89	1.69	2.44	1.62	1.56	1.63
2012-10	4.47	4.03	4.29	3.58	3.64	2.29	2.25	2.88	2.15	2.39	2.69	2.73	2.70	2.25	2.34

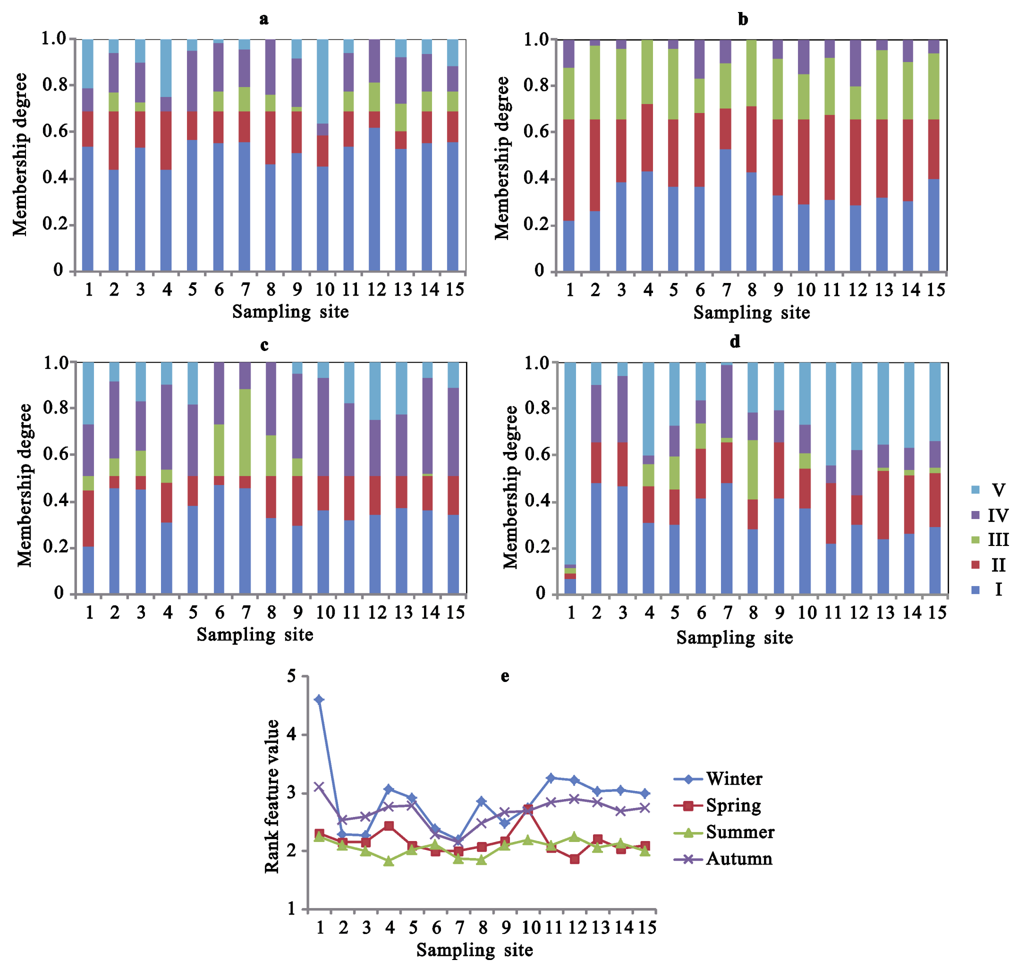

Fig. 2 Membership degree of 15 sampling sites in spring (a), summer (b), autumn (c) and winter (d) to five water quality classes and rank feature value based on the IFVE model (e)

7, 8, and 15 were classified as 'good', with other sites classified as 'medium'. In autumn, however, Site 1 had the worst water quality status ('poor'), whereas the other sites had a water quality of 'medium'. The spatial variations in spring and summer were also insignificant, whereas Site 1 had the worst water quality in winter and autumn (Fig. 2).

Notable inter-annual variations can be observed in Fig. 3 particularly in 2011 and 2012. In 2009, Site 10 yielded 'poor' water quality, whereas other sites were classified as 'medium'. The water quality in all the sampling sites was 'medium' in 2010. In 2011, Site 1 was considered as 'bad', Sites 4, 5, 7, and 11–15 were considered as 'poor', and the remaining sites were considered as 'medium'. Water quality in 2012 was the best among the four years, with only Site 1 classified as 'poor'. Site 4 was in 'medium' condition, whereas the other sites were 'good'. Furthermore, water quality in Site 1 had clearly degraded since 2011, i.e., from 'medium' to 'bad' and 'poor' because of excessive TN and TP loadings. Water quality in 2011 was the worst among the four years investigated, with nine sites having 'bad' or 'poor' condition. This finding could be attributed to the significantly fluctuating TN levels in 2011 for all the 15 sampling sites, and information entropy emphasizing the indicator whose value fluctuated the most (Liu *et al.*, 2010). Thus, the constant weight of TN was established as larger (0.39) than those of the other indices (0.13–0.18). Moreover, TN exceeded the threshold in several sites, thereby degrading the average results to 'bad' or 'poor'.

3.3 Overall water quality evaluation for Poyang Lake

To gain a full picture of water quality variations in Poyang Lake, monthly, inter- and intra-annual average values of water quality parameters were calculated for the entire Poyang lake. The rank feature value was plotted for the entirety of Poyang Lake for each sampling month (Fig. 4). In general, January (winter) had a relatively high rank feature value, which indicated bad water quality ('medium' in most of the sampling months),

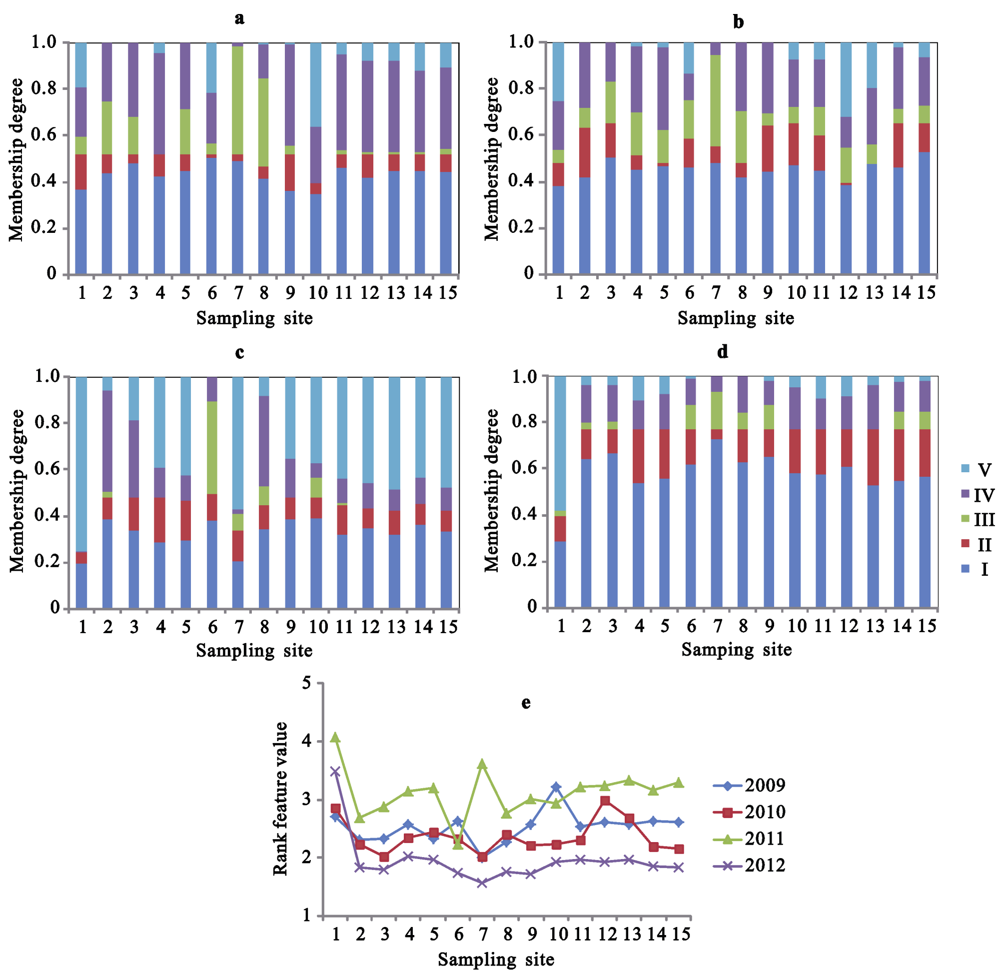

Fig. 3 Membership degree of 15 sampling sites in 2009–2012 (a–d) to five water quality classes and rank feature value obtained using the IFVE model (e)

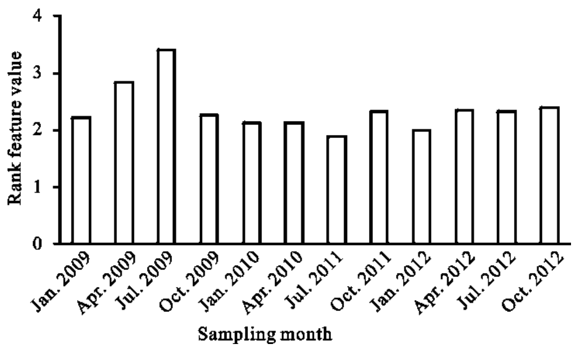

Fig. 4 Rank feature value in different sampling months in Poyang Lake

whereas in July 2009 and 2012, water quality was 'good'. Two months (January 2010 and 2012) had certain indices that exceeded the thresholds, thus variable weights were triggered to consider the 'bucket effect'.

Seasonal and annual membership degrees to five water quality classifications for the entire lake are presented in Fig. 5. Seasonally, water quality in the Poyang Lake was determined as 'poor' in winter. Summer was classified as 'good', whereas other seasons were classified as 'medium'. Meanwhile, inter– annual water quality exhibited the same trend and was classified as 'medium' for each sampling year. This result occurred because combining water quality data from diverse monitoring sites and months might homogenize discrepancies among datasets.

3.4 Comparison of IFVE and IFE models

To compare the evaluation results of the IFVE and IFE model, water quality data in Jan. 2010 and Jul. 2011 were used for examples (Fig. 6). First, water quality in Jan. 2010 was evidently much worse than that in Jul. 2011 according to both methods. For Jan. 2010, the overall water quality was identified as deteriorate in most sampling sites using both models. Moreover, a clear distinction could be observed that the IFVE model increased the effect of awful indices, thereby making it more legible to judge water quality grade. Meanwhile, the water quality states in July 2011 were all classified to 'good' and 'medium' using both models, with few indices exceeding their standards. When the water quality parameters did not exceed the threshold, the 'bucket effect' was excluded and the results of the IFVE model were identical to those of the IFE model (Figs. 6c, 6d). Therefore, the IFVE model, which considers the synthetic contribution of each index to holistic water quality and the bucket effect of key indices, is more efficient than the ordinary IFE model.

4 Discussion

4.1 Performance of IFVE model

According to the national surface water environmental quality standards of China (Table 1), water quality of Poyang Lake could be classified as good (class I, II) in terms of DO, COD_{Mn} and NH_4^+–N. However, it might be polluted in terms of TN and TP concentrations. Therefore, determining water quality solely on spatial or temporal basis by separately examining the fluctuations of individual variables is impractical (Beamonte Córdoba *et al.,* 2010). In addition, concentration values that are close or far from the threshold are considered under the same class in the IFE model. By contrast, the IFVE model can fully examine the contribution of each index to overall water quality and consider the possible bucket effects of extremely poor indices. Considering that the information entropy method emphasized the influences of significantly fluctuating indicators (Liu *et al.*, 2010), we assigned a diverse constant weight for each sampling site and season. Consequently, variable weights were determined based on the index values and

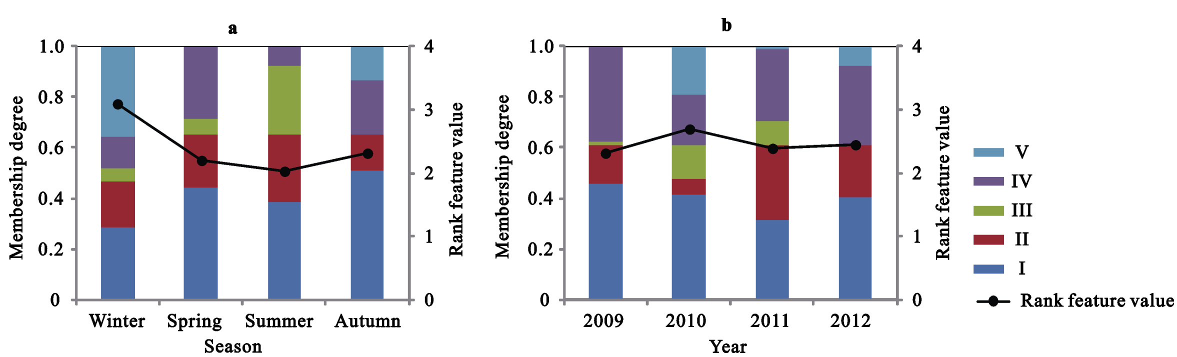

Fig. 5 Seasonal (a) and annual (b) membership degree to five water quality classes and rank feature value for Poyang Lake

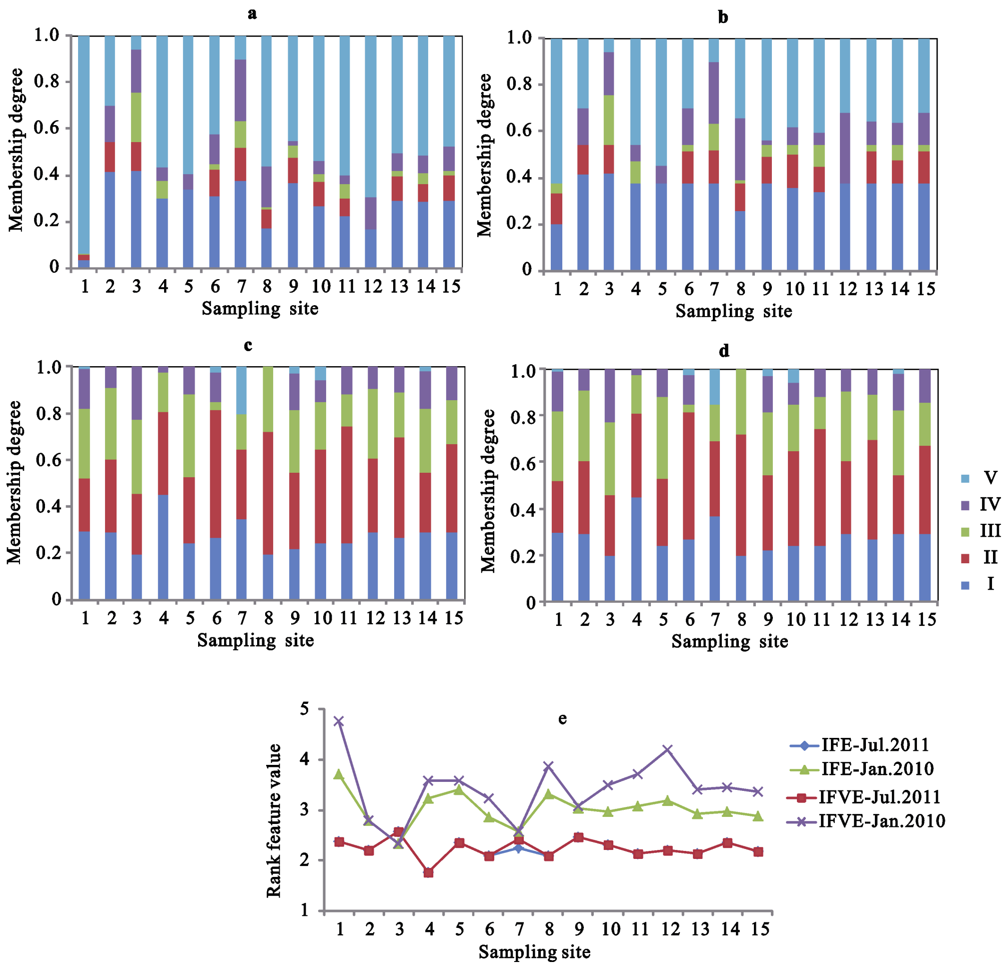

Fig. 6 Water quality evaluation results using IFVE (a: Jan. 2010; c: Jul. 2011) and IFE models (b: Jan. 2010; d: Jul. 2011), and rank feature vale for the Poyang Lake

their corresponding thresholds. This method focuses on the bucket effect of the indices that exceed their standards, thereby adjusting their weights to punish the indices. The more deteriorated the indices are, the harsher the punishment will be. When none of the indices exceeded their thresholds, the evaluation results would be in accordance with the IFE model. TN and TP were identified as the major pollutants in Poyang Lake by examining the variable weights. Accordingly, the IFVE model will be more effective for evaluating water quality status.

The evaluation of the entire lake may provide a general impression of water quality. However, the neutralization of water quality data from the 15 sampling sites and the seasons may downplay the discrepancies among the data, which obscures a huge amount of useful information. Therefore using a smaller evaluation scale is recommended to obtain more accurate evaluation results.

4.2 Implications of variations in water quality parameters

All the 11 common water quality variables were significantly correlated with the seasons. As expected, summer displayed the highest T and SD, whereas winter presented the highest levels of EC, SS, TN, TP and NH_4^+–N. This finding could be explained by the particular hydrological process caused by geographical location and climate, which resulted in large variations in temperature, wind speed, discharge and flow velocity in Poyang Lake throughout the year. The annual fluctuations of variables showed improvement in 2012 after a deteriorating trend from 2009 to 2011. This result indicated that pollution at Poyang Lake had been increasing annually and hydrological status directly affected the concentration of pollutants. For example, 2011 was a typically dry year with an average water level of 10.96 m, and considerably less freshwater flow into the lake. Moreover, the amount of rainfall in 2011 decreased by 49% from the previous year, and the sharp transformation from drought to flooding resulted in an instantaneous surface runoff, in which substantial nutrients flowed into the lake (Xia *et al.*, 2015). Meanwhile, 2012 was a typical high-flow year (with an average water level of 13.74 m) compared with 2011.

Through our examination of spatial variations, Site 7 had the best water quality, and this result could be attributed that it is located downstream of the Zhelin Reservoir, and it receives few pollutants from the Xiushui River and has a relatively high flow velocity. Meanwhile, Site 8 presented higher Chl-a concentrations than the other sites, which could be attributed to the aquaculture in a subsidiary lake called Bang Lake.

4.3 Spatial and temporal variations of water quality

Spatially, Sites 1, 10 and 13 had a relatively deteriorated water quality because three to four months of samples were classified as 'poor' or 'bad' using IFVE model. As previously hypothesized, anthropogenic activities, such as industrial processes, dredging, and aquaculture, may be the main causes. In particular, the water quality in Site 1 underwent significant changes from 'medium' in 2009, and 2010 to 'poor' and 'bad' in 2011 and 2012. This change may be attributed to the Raohe River having the highest pollutant concentrations among the five main tributaries of Poyang Lake (Duan *et al.*, 2016), with average fluxes of 0.54 kg/s and 0.05 kg/s for NH_4^+–N and TP, respectively from 2009 to 2011, which were approximately seven and two times higher than the values of the Xiushui River (Li *et al.*, 2016). In addition, our field survey showed that year-round dredging activities near Site 1 might significantly change the topography of the lakebed and dredge up substantial amounts of sediments. Site 13 is situated in Hamashi, where a large amount of sewage is released by Jiujiang Fiber Corporation and several cement plants (Zhu *et al.*, 2008). It is also the largest sand trading center in Poyang Lake. Site 10 is notable for its complex topography and hydrological conditions, which may generate a vortex (Yin and Zhang, 1987) that may hinder the diffusion of nearby pollutants.

Temporal analysis showed that the hydrological status and the effluents discharged into the lake might be the key factors that influenced water quality in various seasons every year. The seasonal water quality in Poyang Lake exhibited the following order: summer > spring > autumn > winter. That is, summer had the best water quality whereas winter had the worst. These findings could be explained by the fact that considerably more discharge was generated from the five tributaries in summer, which effectively diluted the contaminants in each site, whereas discharge decreased substantially in winter. The impoundment of the Three Gorges Dam also generated a large flow gradient from Hukou to the Yangtze River, which further weakened the self-purification capability of Poyang Lake (Liu *et al.*, 2010; Wu *et al.*, 2011). By contrast, water levels were relatively low in winter and bottom sediments were dredged up by waves, thereby releasing a substantial amount of nutrients into the water (Sondergaard *et al.*, 2001; Hu *et al.*, 2011). Inter-annual water quality evaluation showed that 2011 exhibited the poorest water quality, whereas 2012 presented the best totally. This is indicated by their wholly hydrological condition. For example, 2011 was known as an extremely dry year, with an average lake water level of 10.96 m whereas 2012 was considered as a wet year, with an average lake water level of 13.74 m.

5 Conclusions

In this study, 11 environmental variables were monitored and analyzed seasonally in 15 sampling sites in Poyang Lake, China from 2009 to 2012. The IFVE model was developed by integrating fuzzy theory, information entropy and variable weights to properly evaluate the spatial and temporal variations of water quality in Poyang Lake. The overall water quality in Poyang Lake was 'medium' from 2009 to 2012. In particular, the water quality near polluted tributaries (e.g., Site 1), industrial activities (e.g., Sites 1 and 13) was 'poor' or 'bad'. Moreover, water quality status was associated with hydrological conditions, with the typically dry year 2011 having the worst water quality among the four years, and summer having the best water quality whereas winter had the worst. Moreover, the main cause of water quality deterioration in Poyang Lake was the excessive input of nutrients such as nitrogen and phosphorus.

Compared with the IFE model, the IFVE model exhibits more advantages in considering any possible bucket effects of key indices, which can be useful in reasonably evaluating the variations in water quality.

The IFVE model is an effective tool for evaluating water quality on small scales and for identifying key variables that indicate water quality deterioration. However, a larger evaluation scale may decrease the accuracy of the IFVE model, for which dangerous factors may be covered by constant weights and data neutralization. The model and evaluation results can offer useful recommendations for environmental protection agencies and decision makers. Further studies on the relationship between pollutant diffusion and hydrological status may improve understanding on temporal variations.

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