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Assessment of the Spatial and Temporal Water Eutrophication for Lake Baiyangdian Based on Integrated Fuzzy Method

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ABSTRACT

Water quality evaluation entails both randomness and fuzziness. Considering that water eutrophication evaluation involves many indices, different classifications and interval values, fuzzy variable sets theory was developed to Lake Baiyangdian as a study case. Taking reference to eutrophication standard of Chinese lakes and local characteristic of Lake Baiyangdian, eutrophication degree of lake was divided into 8 levels. Total phosphorus, total nitrogen, and COD_{Mn} were selected as evaluation indices in this research. Based on the measured data, index feature value matrix of sample was built. Index weights were determined by means of pure threshold value method. Relative membership degree of each index to each classification was calculated with relative difference function model. Then the stability of feature value of classification corresponding was received by the comprehensive calculation with the relative membership degree and index weights. The results show that the proposed models are effective tools for generating a set of realistic and flexible optimal solutions for complicated water quality evaluation issues. It concluded that the model was reasonable and practical.

Keywords: Eutrophication Evaluation; Fuzzy Method; Spatial Variation; Temporal Variation; Lake Baiyangdian

1. Introduction

Lake Baiyangdian is the largest fresh water lake and natural wetland in north China. The lake plays an important role in balancing the ecosystem there. It is described as the "Kidney of North China" and serves many environmental and economic services. The lake area is divided into various sizes and shapes by 39 villages, over 3700 ditches and 80 km^2 of reeds. The ditches in the lake area are in crisscross patterns. The geographical feature of reed marsh, lotus ponds and fishing villages is unique throughout China. Lotus ponds and boundless reed marshes are the special sights of the lake, thus it enjoys the good reputation of "North China Pearl".

While appearing pristine beauty in parts, Lake Baiyangdian is under assault from a variety of sources, most notably industrial and domestic wastewater emptied upstream, the holding back of replenishing waters into reservoirs by upstream communities, and local fish farming [1,2]. In particular, Lake Baiyangdian has 39 in-lake villages, which are surrounded by water in the lake, and 44 semi-in-lake villages, which are partly surrounded by water in the lake. An estimated 100,000 persons live in the in-lake villages and another 100,000 persons in the surrounding areas of the lake. The low water level, rotten organic substance underwater, and other factors also led to deterioration of water quality and shrinkage of the lake area in recent years.

All the functions depend on the water quality which should be kept at a certain level to maintain a well-balanced environment in terms of its physical, chemical and biological variables. Water-quality deterioration and eutrophication are general problems in the world lake and have acquired more and more attention from the public and government. The introduction of large quantities of nutrients, mainly nitrogen and phosphorus to lake waters can cause eutrophication problems [3]. Eutrophication is the most widespread water quality problem in China and many other countries in the last few decades [4]. Eutrophication is also becoming a sharp problem to Lake Baiyangdian due to the increase of nutrients from upstream and in-lake villages. As biological response to excess nutritive salt importing into the lake, the increase of biomass, in particular aquaplant, in Baiyangdian have weaken the water functions and threatened the biologic health.

the cleanup and repristination of Lake Baiyangdian is currently a topic of increasing concern by Chinese government and local environmental protection bureau for its special location and ecological significance. Actually the lake eutrophication, influenced by many factors, is a typical multi-criteria decision-making.

As an important basic research subject, building appropriate model and accurately evaluating the eutrophication degree is the basis and premise for the control of lake eutrophication [5]. Eutrophication evaluation is such a problem that involves different indices, many classifications and interval values. During eutrophication evaluation, the evaluative result of each index is always incompatible and independent. And directly basing on the evaluation of one index will cause information omission and even wrong result [6].

In the frame of the present work, a study was performed for select certain evaluation indices and mathematic method. Different methods had been evaluated the water quality [7-9]. Fuzzy synthetic evaluation is a modified and corrected version of conventional synthetic evaluation [10,11]. The fuzzy evaluation is given in accordance with the evaluation criteria and themeasured values to evaluate the fuzzy transformation of things in a way. Fuzzy variable evaluation method can effctively deal with the influence of evaluation standard interval values and set up the comprehensive evaluation model to fulfill the comprehensive evaluation to water environment [12, 13].

The aim of this paper is to explore the use of fuzzy classification to eutrophication modelling in Lake Baiyangdian. More specifically, we use fuzzy inference to recognize vague patterns in a set of spatial and temporal data. This evaluation aimed to ascertain the eutrophication problems and then to improve the measures of comprehensive treatment for Baiyangdian.

2. Objectives and Method

2.1. Study Area

The study area is located in Hebei Province (38.850˚N, 116.000˚E). This shallow lake is disk-shaped with surface area 366 km^2 and water depth 1 - 2 m. The lake lies in the middle reaches of the Daqinghe River basin and ultimately discharges into the Bohai Gulf, Yellow Sea. Much of the upstream catchment totaling 31,500 km^2 lies within Baoding municipality. While nine rivers and/or channels flow into Lake Baiyangdian, only two have regular but decreasing flows, namely, Fuhe and Juma River [14]. Water systems of Baiyangdian area was shown in **Figure 1**.

2.2. Sampling Points and Monitoring Data

The monitoring study was carried out with water samples. Eight water-quality sampling sites were established. Sampling sites in Lake Baiyangdian were shown in **Figure 2**.

The monitoring data were collected including COD_{Mn}, TP, TN concentrations every month from 1996 to 2008. The spatial-temporal eutrophication characteristic analysis will be helpful to watershed management.

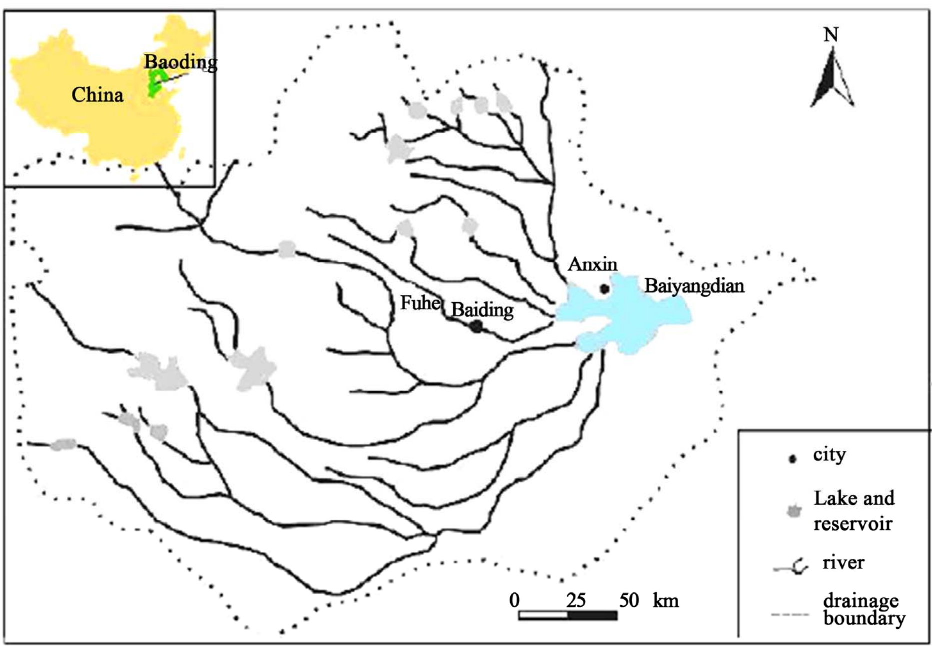

Figure 1. Map of the studied area and water systems of drainage area.

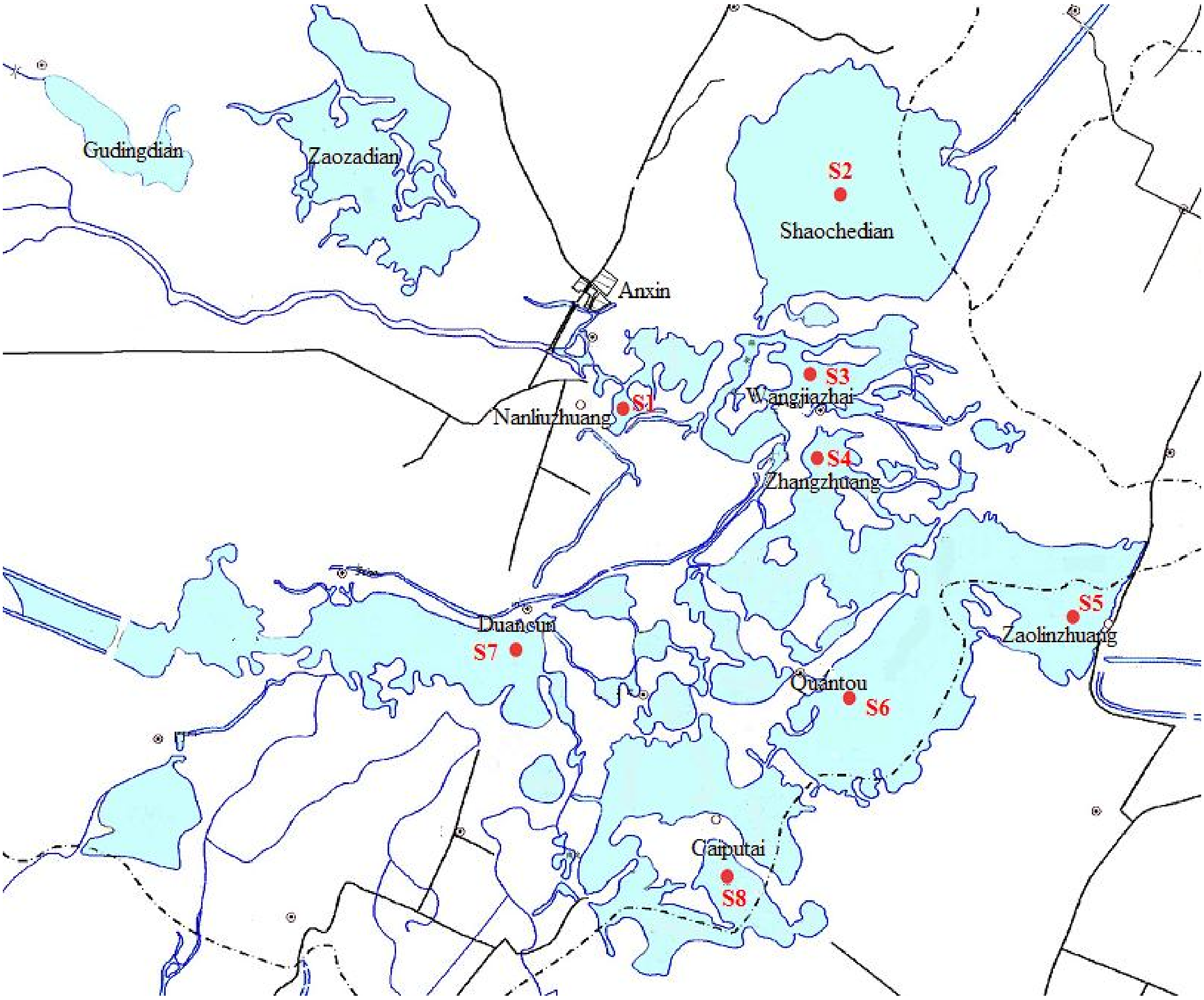

Figure 2. Distribution of sampling sites in research area.

2.3. Evaluation Method

2.3.1. Fuzzy Evaluation Method

The fuzzy evaluation includes the following steps [15].

1) Set the collection of the factors U = {U1, U2, U3, ···, Un}, where U is the measured values of the evaluation factors;

2) Set the collection of the evaluation standard V= {V1, V2, V3, ···, Vn}, where V is corresponded to the pollution of the water quality standard classification;

3) Determine index weight A;

4) Determine fuzzy matrix R;

5) Calculate evaluation matrix B and get a result.

2.3.2. Evaluation Standard

Select the major pollution factors total phosphorus (TP), total nitrogen (TN), COD_{Mn} as an evaluation to determine the collection of the factors U = $\{U_{TP}, U_{TN}, U_{COD}\}$, and in accordance with the water quality data of the year 1996 to 2008.

Based on the accepted method and actual feature, evaluation standard was classified into eight levels and listed in **Table 1**. Determine the evaluation standard $V=\{V_1, V_2, V_3, \cdots, V_8\}$.

2.3.3. Index Weight A Determination

At present, there are many methods to calculate the weight of pollution factors, such as entropy value method, equal weight method and pure threshold value method. In this work, standard assignment method was chosen. It is calculated by the following method.

$$A_i = \frac{X_i / S_i}{\sum X_i / S_i}$$

where A_i is the weight of the pollution factors *i*; S_i is the arithmetic mean of the *i* kinds of all the standard; and X_i is the measured values of the factors *i*.

Table 1. Evaluation classification standard of water eutrophication in Baiyangdian.

Level	Eutrophic classification	TP (mg/L)	TN (mg/L)	COD_{Mn} (mg/L)
1	Oligotrophic	0 - 0.0046	0 - 0.30	0 - 0.48
2	Mesotrophic	0.0046 - 0.010	0.30 - 0.60	0.48 - 0.96
3	Lower-eutrophic	0.010 - 0.023	0.60 - 1.00	0.96 - 1.80
4	Eutrophic	0.023 - 0.050	1.00 - 1.50	1.80 - 3.60
5	Upper-eutrophic	0.050 - 0.11	1.50 - 2.00	3.60 - 7.10
6	Seriously eutrophic	0.11 - 0.25	2.00 - 3.00	7.10 - 14.0
7	Hyper1eutrophic	0.25 - 0.55	3.00 - 4.60	14.0 - 27.0
8	Seriously hyper-eutrophic	0.55 - 1.20	4.60 - 10.0	27.0 - 54.0

Then $A = \{A_{TP}, A_{TN}, A_{COD}\}$.

2.3.4. Comprehensive Relative Membership Degree Determination

Comprehensive relative membership degree was gotten as follows.

$$\text{When } j = 1, r_{ij} = \begin{cases} 0 & X_i \geq S_{i(j+1)} \\ \dfrac{S_{i(j+1)} - X_{ii}}{S_{i(j+1)} - S_{ij}} & S_{ij} \leq X_i \leq S_{i(j+1)} \\ 1 & X_i \leq S_{ij} \end{cases}$$

When $j = 2, 3 \cdots n-1$,

$$r_{ij} = \begin{cases} 0 & X_i \leq S_{i(j-1)}, X_i \geq S_{i(j+1)} \\ \dfrac{X_i - S_{i(j-1)}}{S_{ij} - S_{i(j-1)}} & S_{i(j-1)} \leq X_i \leq S_{ij} \\ \dfrac{S_{i(j+1)} - X_i}{S_{i(j+1)} - S_{ij}} & S_{ij} \leq X_i \leq S_{i(j+1)} \end{cases}$$

$$\text{When } j = n,\ r_{ij} = \begin{cases} 0 & Xi \leq S_{i(j-1)} \\ \dfrac{X_i - S_{i(j-1)}}{S_{ij} - S_{i(j-1)}} & S_{i(j-1)} \leq X_i \leq S_{ij} \\ 1 & X_i \geq S_{ij} \end{cases}$$

where j is the level of pollution; X_i is the first i in the environment of pollutants measured values; S_{ij} is the kinds of pollutants that the first i-level for the first j standards values.

2.3.5. Fuzzy Matrix *R* Determination

Input the data of every year into above membership degree determined, then their membership and the fuzzy evaluation matrix *R* were established.

$$R = \begin{vmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ r_{21} & r_{22} & r_{23} & r_{24} \\ r_{31} & r_{32} & r_{33} & r_{34} \end{vmatrix} \begin{matrix} TP \\ TN \\ COD_{Mn} \end{matrix}$$

2.3.6. Evaluation Matrix B Determination and Get the Result

After establishment of the A and R, the fuzzy comprehensive evaluation can calculate the matrix B, namely B = AR. According to the principle of the largest degree of membership, if in the matrix $B = \{b_1, b_2, \cdots, b_n\}$ in the presence $bj = \max\{ b_1, b_2, \cdots, b_n\}$, then the level should be evaluated for the j-level. The computation use of "∧ and ∨" that is, multiplication getting a lest value then adds getting biggest value.

3. Results and Discussion

3.1. Dominant Pollutants in Lake Baiyangdian

The annual index weights of pollution factors in 1996 to 2008 were determined and listed in **Table 2**. The index weight results in **Table 2** indicated that TN had largest impact in most of year, so TN was the dominant pollutants throughout the year for the eutrophication in Baiyangdian.

3.2. Spatial Change of Water Eutrophication in Lake Baiyangdian

The eutrophic level of all sites in Lake Baiyangdian in 1996 and 2008 was calculated by fuzzy evaluation method separately. Evaluation results were shown in **Table 3**.

Baiyangdian presented significantly regional patterns.

Table 2. Weight of pollution factors.

Year	TP	TN	COD_{Mn}
1996	0.19	0.57	0.24
1997	0.29	0.46	0.25
1998	0.24	0.52	0.24
1999	0.45	0.35	0.20
2000	0.34	0.48	0.18
2001	0.43	0.36	0.21
2003	0.20	0.35	0.45
2004	0.32	0.36	0.32
2005	0.20	0.52	0.28
2006	0.21	0.55	0.24
2007	0.28	0.48	0.24
2008	0.25	0.52	0.23

Table 3 Evaluation results in different monitoring sites.

Year	Site	Calculation results of matrix B								Level
		1	2	3	4	5	6	7	8	
1996	1	0	0	0	0	0	0.10	0.24	0.66	8
	2	0	0.05	0.15	0.63	0.10	0	0	0	4
	3	0	0	0.26	0.44	0.51	0	0	0	5
	4	0	0.03	0.42	0.02	0.51	0	0	0	5
	5	0.02	0.30	0.10	0.44	0.56	0	0	0	5
	6	0	0.36	0.18	0.52	0.26	0	0	0	4
	7	0	0	0.45	0.48	0.42	0	0	0	4
	8	0	0.35	0.34	0.53	0.47	0	0	0	4
2008	1	0	0	0	0	0.06	0.06	0	0.61	8
	2	0	0	0	0.38	0.48	0.42	0	0	5
	3	0	0	0.12	0.36	0.5	0.32	0	0	5
	4	0	0	0.36	0.36	0.51	0.23	0	0	5
	5	0	0	0.30	0.18	0.58	0.40	0	0	5
	6	0	0	0	0.42	0.45	0.06	0	0	5
	7	0	0	0.09	0.46	0.47	0.09	0	0	5
	8	0	0	0.37	0.30	0.51	0.04	0	0	5

Site 1 was the most hypereutrophic site among Baiyangdian obviously. It was the catchment basin of Fuhe River from Baoding City. Baoding located in the upper reaches of Lake Baiyangdian, discharged 20 t of sewage water by two sewage treatment plants and citizens each day.

Other sites were in eutrophic or upper-eutrophic levels. Ultimately, these sites were in upper-eutrophic according the results of 2008. Water eutrophication in Baiyangdian trended to intensify. Seemingly, this conclusion was not corresponding to the enormous effort to Baiyangdian by government and researchers. The release mechanism of nutrimental salts in shallow lake was more complex. This essential feature of shallow lake determined the hysteresis of water quality, so sustaining and extending protection steps were essential to Baiyangdian.

Table 4. Evaluation results different water periods of Lake Baiyangdian.

	1994	1995	1996	1997	1998	1999
Flat-water period	6	4	6	6	7	7
Dry-water period	6	5	6	6	7	6
Wet-water period	4	4	4	6	6	7

3.3. Temporal Change Chatacter of Water Eutrophication in Lake Baiyangdian

The eutrophic level of Lake Baiyangdian from 1996 to 2008 years was evaluated by above method. The calculation results indicated the eutrophic levels were between level 5 to 7. Baiyangdian was in a state of seriously eutrophic level during the last decade to now. Actually, many protection and restoration measures have been taken to control the eutrophication. The eutrophic level showed the vulnerability and liability of eutrophication in shallow lakes environment.

3.4. Comparison of Temporal Variation

May, August and October were corresponded to dry-water period, wet-water period and flat-water period respectively. The eutrophication status of different water periods from 1996 to 1999 were calculated and the results were shown in **Table 4**.

The results in **Table 4** exhibited the significantly temporal variation in Baiyangdian. Eutrophic degrees were changed between Level 4 to Level 7. From **Table 4**, the lake eutrophication was more serious in the dry period and alleviative in the wet period.

4. Conclusions

It is feasible to evaluate the degree of water eutrophication by this method. We can get a better understanding of the situation of Baiyangdian by calculating the eutrophication of the lake and later provide the basis for the management of Baiyangdian.

The degree of eutrophication of Baiyangdian is closely relevant to the factor TN and COD_{Mn}, so TN and COD_{Mn} should be studied to improve the situation of Baiyangdian.

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