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The Application of the Evidence-Cloud Model On the Water Quality Evaluation

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Abstract

The water quality assessment has tremendous significance for water pollution prevention. First, the DO (dissolved oxygen), permanganate index, TN (total nitrogen), TP (total phosphorus) as well as NH₃-N are adopted as the evidence body. Their basic probability is determined using the cloud theory. Secondly, the synthetic probability of different sections is calculated based on the evidence theory. Relatively to the traditional matter-element extension model, it can improve the predictive accuracy and determine the certainty reliability of different evidence bodies, the difference of importance between other evidence bodies can be reflected; so the proposed theory can well predict the grade criterion which are interval form. Conclusions are drawn that the suggested method is entirely consistent with the actual investigation; it enhances the predictive efficiency of water quality and can provide a new approach and think for the water quality assessment in the future.

Keywords: Quality evaluation; Water ; Evidence-cloud Theory; Application.

Introduction

Groundwater resources serve as the primary source of drinking water for residents and water for industrial and agricultural use in China. They are a crucial foundation for ensuring domestic water supply, supporting economic and social development, and maintaining ecological and environmental health[1-2]. Currently, the sources and types of groundwater pollutants in China are becoming increasingly complex, posing a severe challenge to the monitoring, supervision, and prevention of groundwater pollution. How to scientifically and reasonably evaluate

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groundwater quality and pollution is the foundation for the prevention, control, and rational exploitation of groundwater pollution[3].

The selection of groundwater quality evaluation indicators is characterized by fuzziness, randomness, and uncertainty [4]. In essence, it involves a process of analyzing deterministic evaluation criteria against uncertain monitoring data[5].Currently, the main methods for water quality assessment include neural network methods[6], single-factor index methods[7], fuzzy comprehensive evaluation methods[8], and grey clustering methods[9], among others. Sun [10] utilized an Elman neural network to evaluate the pollution sources and water quality grades of the Xihe Reservoir, and found that the water quality during the dry season was better than that during the wet season; Liu et al. [11] employed the fuzzy comprehensive evaluation method to quantitatively assess the groundwater quality in closed mines, and the results indicated that the water quality in the closed mining areas of the Longyong Coalfield was relatively poor; Xue Weifeng et al. [12] utilized principal component analysis and the fuzzy comprehensive evaluation method to assess the groundwater quality in Dalian City, and found that the comprehensive control indicators for water quality were total hardness, total dissolved solids, and ammonia nitrogen;Meng Linghua et al.[13] combined the improved Nemerow comprehensive index evaluation method with the worst-case indicator discrimination method, addressing the issues of

missing and jumping water quality categories inherent in the traditional Nemerow index method, as well as the overly pessimistic results of the worst-case indicator discrimination method; Gong Yicheng et al. [14] proposed a combined evaluation model integrating projection pursuit and fuzzy matter-element analysis for groundwater quality assessment. This model enables the analysis of high-dimensional, non-normal, and nonlinear data, while also facilitating qualitative analysis of water quality change trends.

These methods have played a certain guiding role in the comprehensive utilization of mine water in water quality assessment. However, due to the limitations of the applicable conditions of various models and on-site data collection, each method has certain shortcomings[15]. For instance, neural networks suffer from issues such as requiring large amounts of learning data, slow convergence rates, and a tendency to get stuck in local minima; while the single-factor index method, although simple to calculate, bases its evaluation solely on the lowest grade, resulting in a relatively one-sided and conservative assessment outcome. The fuzzy comprehensive evaluation method involves complex calculations and exhibits strong subjectivity in determining the weight vectors of indicators; while the grey clustering method entails a massive computational workload and is also highly subjective[16]. In summary, while there are numerous methods available

for water quality assessment, each has certain deficiencies in addressing the fuzziness, uncertainty, and randomness associated with the selection of water quality indicators.

To overcome the above deficiencies, the cloud model is applied to handle the uncertain transformation between qualitative concepts and quantitative descriptions[17-18], and the evidence theory demonstrates notable advantages in processing "uncertain" and "unknown" information [19-20], serving as a powerful tool for information fusion. This paper conducts a combined evaluation of the two methods by obtaining evidence through the cloud model and utilizing evidence theory for information fusion, and final global sensitivity analysis is performed through defuzzification processing.

The manuscript is organized as follows: in Section 2, Engineering background is introduced; in Section 3, methodology based on the Evidence-cloud model are presented; in Section 4, the assessment model is constructed, and the assessment results are analyzed; in Section 5, conclusions are drawn.

Materials and Methods

Study Area

The study area is located in Zibo City, Shandong Province, covering an area of approximately 20 km², and it involves multiple industries such

94 as petrochemical engineering and chemical manufacturing. The region
95 enjoys a warm-temperate continental monsoon climate, characterized by
96 mild weather, distinct seasons, abundant sunshine, moderate precipitation,
97 a relatively short frost period, and high evaporation. The average annual
98 temperature is 12.5°C, and the multi-year average precipitation is 587
99 mm. The geomorphic unit within the area belongs to the piedmont alluvial
100 plain, featuring a flat terrain. There are no geological phenomena such as
101 faults or unfavorable tectonic structures within the region that could
102 affect the stability of engineering projects. It represents a geological unit
103 with simple and relatively stable tectonic conditions. The groundwater
104 type in the area is unconsolidated rock pore water, which is continuously
105 distributed. The subject of this study is shallow pore water, with lithology
106 mainly consisting of silt, silty fine sand, and silt. The thickness varies
107 greatly, and the water-yielding property is relatively weak. The primary
108 recharge sources include atmospheric precipitation, surface water
109 infiltration, irrigation return flow, and subsurface lateral runoff. The
110 lithology of the vadose zone is predominantly silty clay, which has
111 relatively poor water permeability and slow infiltration rates. Samples
112 were collected from 10 monitoring wells, the distribution of which is
113 shown in Figure 1.

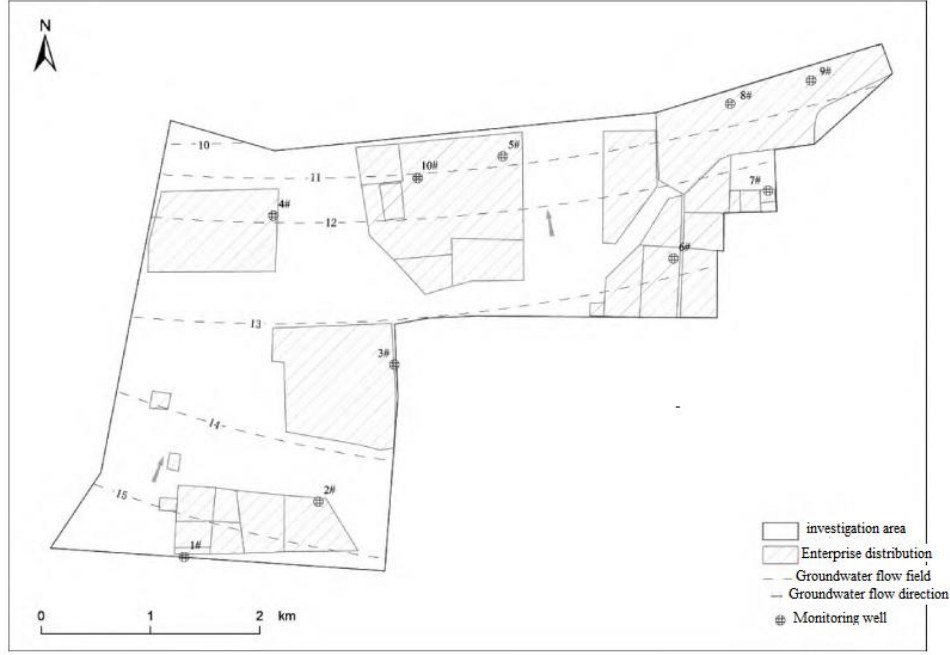


Figure 1 Monitoring well distribution

Methodology

(1)The cloud model

As an uncertainty transformation model, cloud model has a great advantage in dealing with fuzzy and random events[21], it is assumed that the quantum field $U = \{x\}$, C is the qualitative concept corresponding to a quantitative interval in U . The Element x is a random implementation of C on U . The value range $[0,1]$ is a random number with a stable tendency.

$$\mu: U \rightarrow [0,1] \forall x \in U \quad x \rightarrow \mu(x) \quad (1)$$

The distribution of x in the Universe U is called as cloud drop, (E_x, E_n, H_e) is three numerical features of the cloud model. Where, E_x reflects the average point of cloud droplets; entropy E_n is the uncertainty measure of qualitative concept; and super-entropy H_e is the uncertainty

measure of entropy, it reflects the degree of cohesion of cloud droplets.

The generation of cloud images involves cloud generators, which are divided into two types: the forward cloud generators and reverse cloud generators.

①The forward cloud generator output cloud

$$y_i = \exp\left[\frac{-(x_i - E_x)^2}{E_n^2}\right] \quad (2)$$

Where, E_x is the expectation value; E_n^2 is the variance. y_i is the degree of certainty that x_i belongs to a certain qualitative concept; then (x_i, y_i) is the cloud droplets. Repeat the process until N droplets are formed to form a cloud.

②The reverse cloud generator computes the E_x formula for the average of the various digital feature samples of the cloud model[22].

$$E_x = \bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (3)$$

(2)The evidence theory

Given an identification framework Θ , the set function m is a mapping on the power set 2^Θ , $m: 2^\Theta \rightarrow [0,1]$, satisfy with the follow conditions:

$$m(\Phi) = 0 \quad (4)$$

$$\sum_{A \subseteq \Theta} m(A) = 1 \quad (5)$$

Where, Φ is a empty set; m is a basic probability assignment function for Θ ; $m(A)$ is the basic belief function or mass function of A , representing the degree of belief in A .

If $A \subseteq \Theta$ and $m(A) > 0$, then A is called as focal element of evidence.

Assuming that E_1 and E_2 are two pieces of evidence of identification frame, respectively. m_1 and m_2 are the basic belief assignment functions corresponding to the two pieces of evidence, respectively. Focal elements are A_1 and A_2 , respectively. By Dempster combination rule $m = m_1 \oplus m_2$, it is defined as[23]:

$$m(A) = \begin{cases} \frac{\sum_{A_1 \cap A_2} m_1(A) m_2(A)}{1 - K} & A \neq \Phi \\ 0 & A = \Phi \end{cases} \quad (6)$$

$$K = \sum_{A_1 \cap A_2 = \Phi} m_1(A_1) m_2(A_2) < 1 \quad (7)$$

Where, K is conflict coefficient.

$1 - K$ is a normalization factor; it assigns all conflicts to the empty set Φ , to ensure that the sum of basic probability assignments equals 1, the belief mass lost on the empty set is proportionally redistributed to non-empty sets via a normalization factor. The magnitude of the conflict coefficient K reflects the degree of contradiction among evidence sources. A larger K indicates greater evidence conflict. When $K = 1$, it signifies complete contradiction between evidences, rendering the combination formula inapplicable.

(3) The procedure of the evidence-cloud model

① The calculation of digital feature based on the cloud model

The each evaluation index has an interval value $[C_{\min}, C_{\max}]$. Therefore, the formula of digital characteristics about the cloud is as follows

$$E_{xij} = \frac{C_{\min}(k) + C_{\max}(k)}{2} \quad (8)$$

$$E_{nij} = \frac{C_{\max}(k) - C_{\min}(k)}{6} \quad (9)$$

$$H_{eij} = \lambda \quad (10)$$

Where, $E_{xij}(k)$, $E_{nij}(k)$ and H_{eij} are expected values, entropy values and super-entropy values of D_{ij} in the k-level Cloud model respectively.

② The calculation of membership degree

Let x_{ij} be the measured value of D_{ij} at T time, x_{ij} in the diagnostic cloud model for each quality level can be obtained according to Equation (11).

$$\mu_{ij}(k) = \exp\left\{\frac{-[x_{ij} - E_{xij}(k)]^2}{2[E'_{nij}(k)]^2}\right\}, k = I, II, \dots, V \quad (11)$$

Where, $E'_{nij}(k)$ is a normal random number with entropy $E_{nij}(k)$ as expectation and $H_{eij}(k)$ as standard deviation.

③ The determination of basic probability assignment

To ensure that the membership degree of evaluation index C_i to safety grade T_j satisfies the definition of a basic probability assignment (BPA), an additional definition of certainty degree must be introduced, namely:

$$\theta_i = 1 - \max(\mu_{ij}) \quad (12)$$

$$m_i(\Theta) = \theta_i \quad (13)$$

$$m_i(T_j) = \frac{(1 - \theta_i)\mu_{ij}}{\sum_{j=1}^5 \mu_{ij}} \quad (14)$$

Where: θ_i denotes the degree of uncertainty in the membership of the i th indicator's eigenvalue to the j th grade; $m_i(\theta)$ represents the uncertainty

measure of the universal set; $m_i(T_j)$ signifies the Basic Probability Assignment (BPA) of the i th influencing factor to the j th risk state.

④The improved dempster-shafer theory fusion

1.The Screening and Processing of Evidence

Evidence within the frame of discernment is screened using an evidence similarity function, support degree, and credibility measure. Subsequently, preprocessing is performed on evidence exhibiting varying degrees of imbalance, errors, or conflicts. Given two pieces of evidence, E_1 and E_2 , under the frame of discernment Θ , with corresponding basic probability assignment functions m_1 and m_2 , and focal elements A_1 and A_2 respectively, the similarity coefficient d_{12} between E_1 and E_2 is calculated as[24]:

$$d_{12} = \frac{\sum_{A_1 \cap A_2 \neq \Phi} m_1(A_1)m_2(A_2)}{\sqrt{(\sum m_1^2(A_1)\sum m_2^2(A_2))}} \quad (15)$$

The support degree $Sup(m_r)$ is calculated using the similarity between evidence sources, which subsequently enables the determination of the credibility measure $Crd(m_r)$. The respective formulas are as follows:

$$Sup(m_r) = \sum_{s=1, r \neq s}^n d_{rs} \quad r, s = 1, 2, \dots, n \quad (16)$$

$$crd(m_r) = \frac{\sup(mr)}{\sum_{r=1}^n \sup(m_r)} \quad r = 1, 2, \dots, n \quad (17)$$

Where, d_{rs} denotes the distance between the r th evidence and the s th evidence; n represents the total number of evidence sources.

After obtaining the credibility of the evidence, the f th piece of conflicting evidence is revised using the correction coefficient F_{dis} , and the basic probability assignment function after the revision is as follows:

$$m'_i(u'_j) = F_{dis} m_i(u'_j), \quad u'_j \subset \Theta \quad (18)$$

$$m'_i(\Theta) = F_{dis} m_i(\Theta) + 1 - F_{dis} \quad (19)$$

$$F_{dis} = crd(m_i) / \max\{crd(m_i)\} \quad (20)$$

2. Sensitivity analysis based on the Monte Carlo simulation

The Spearman rank correlation coefficient is a measure of global sensitivity analysis (GSA) that can determine the correlation between two variables and reveal the sensitivity between input and output factors, its expressions are [25-26]:

$$GSA(D_{ij}) = \frac{\sum_{q=1}^Q (R(x_i^q) - \bar{R}(x_i^q))(R(t^q) - \bar{R}(t^q))}{\sqrt{\sum_{q=1}^Q (R(x_i^q) - \bar{R}(x_i^q))^2} \sqrt{\sum_{q=1}^Q (R(t^q) - \bar{R}(t^q))^2}} \quad (21)$$

Where, q is q th iteration, $q = 1, 2, \dots$. $R(x_i^q)$ is the rank of observations of assessment index D_{ij} ; $\bar{R}(x_i^q)$ is the mean value of $R(x_i^q)$; $R(t^q)$ is the rank of the q th assessment result t ; $\bar{R}(t^q)$ is the mean value of $R(t^q)$.

The determination of the evaluation index

To assess the water quality accurately, DO (dissolved oxygen), permanganate index, TN (total nitrogen), TP (total phosphorus), and $\text{NH}_3\text{-N}$ (ammonia nitrogen)—are selected as the evaluation indicators for this study. Its monitoring datum is shown in Table 1; the five indicators are classified into five grades, shown in Table 2. They are, respectively, I

(perfect), II(good), III(medium), IV(bad) and V(very bad).

Table 1 The monitoring datum

Cross section	DO	permanganate index	TN	TP	NH ₃ -N
1#	7.38	1.66	1.43	0.04	0.04
2#	7.89	2.22	1.58	0.06	0.01
3#	8.36	1.63	1.14	0.06	0.08
4#	6.27	7.53	1.54	0.13	0.08
5#	7.79	1.57	0.85	0.02	0.02
6#	7.58	2.38	1.96	0.06	0.13
7#	2.39	2.35	3.45	0.09	0.06

Table 2 The classification standard

The level of water quality	DO	permanganate index	TN	TP	NH ₃ -N
I	≥7.5	≤2	≤0.2	≤0.02	≤0.15
II	(6 7.5]	(2 4]	(0.2 0.5]	(0.02 0.1]	(0.15 0.5]
III	(5 6]	(4 6]	(0.5 1]	(0.1 0.2]	(0.5 1]
IV	(3 5]	(6 10]	(1 1.5]	(0.2 0.3]	(1 1.5]
V	(2 3]	(10 15]	(1.5 2]	(0.3 0.4]	(1.5 2]

The assessment frame

The cloud-improved evidence theory method integrates the uncertainty of information, comprehensively considers the effects of multiple quality-inducing factors, and fuses the evaluation results onto the decision-making level through layer-by-layer reasoning, aiming to obtain more accurate and reliable quality perception results and facilitate water quality assessment. The process of the quality assessment model is illustrated in Figure 2.

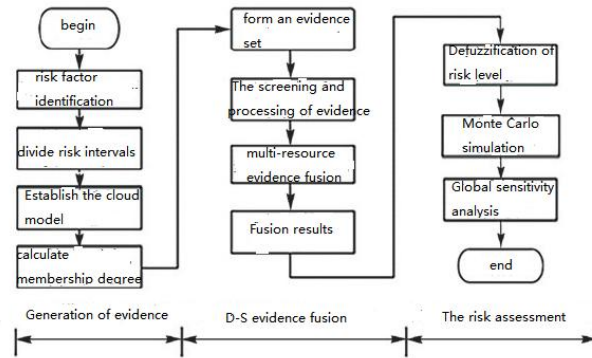


Figure 2. The evaluation flowchart

Results and Discussion

(1) The construction of assessment model

Based on the Table 2 and Equations (8)-(10), three feature parameters of cloud model are shown in Table 3.

Table 3 The feature parameter of cloud model

grade indicator	I	II	III	IV	V
DO	(11.25 1.875 0.01)	(6.75 0.25 0.01)	(5.5 0.167 0.01)	(4 0.33 0.01)	(2.5 0.167 0.01)
permanganate index	(1 0.33 0.01)	(3 0.33 0.01)	(5 0.33 0.01)	(8 0.67 0.01)	(12.5 0.833 0.01)
TN	(0.1 0.033 0.01)	(0.35 0.05 0.01)	(0.75 0.0833 0.01)	(1.25 0.083 0.01)	(1.75 0.083 0.01)
TP	(0.01 0.0033 0.01)	(0.06 0.0133 0.01)	(0.15 0.0167 0.01)	(0.25 0.0167 0.01)	(0.35 0.0167 0.01)
NH ₃ -N	(0.075 0.025 0.01)	(0.325 0.0583 0.01)	(0.75 0.0833 0.01)	(1.25 0.0833 0.01)	(1.75 0.0833 0.01)

Figure 3 displays the cloud model distribution curve of factor TN.

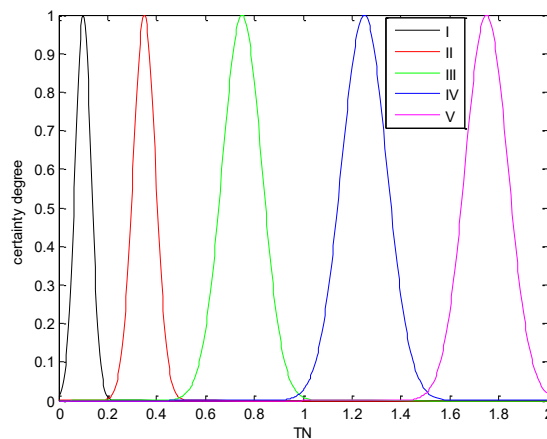


Figure 3. Cloud model distribution curve of factor TN

Substitute the data of the evaluated section into the cloud model to calculate the belief degrees for each grade and the belief matrix transformed from the standard cloud. Taking 1# Section as an example for calculation, the belief matrix obtained from the cloud model can be derived.

$$U = \begin{bmatrix} I & II & III & IV & V \\ 0.1188 & 0.0418 & 0 & 0 & 0 \\ 0.1353 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.0968 & 0.0006 \\ 0 & 0.3228 & 0 & 0 & 0 \\ 0.3753 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The basic probability assignment function according to Equations (12) - (14) is calculated, that is, the result of converting the belief matrix into evidence:

$$U' = \begin{bmatrix} I & II & III & IV & V & \Theta \\ 0.0879 & 0.0309 & 0 & 0 & 0 & 0.8812 \\ 0.1353 & 0 & 0 & 0 & 0 & 0.8647 \\ 0 & 0 & 0 & 0.0962 & 0.0006 & 0.9032 \\ 0 & 0.3228 & 0 & 0 & 0 & 0.6772 \\ 0.3753 & 0 & 0 & 0 & 0 & 0.6247 \end{bmatrix}$$

Based on Equation (15), the similarity coefficient matrix can be expressed as:

$$d = \begin{bmatrix} 1 & 0.9978 & 0.9889 & 0.9127 & 0.9035 \\ 0.9978 & 1 & 0.9824 & 0.8918 & 0.9265 \\ 0.9889 & 0.9824 & 1 & 0.8976 & 0.8524 \\ 0.9127 & 0.8918 & 0.8976 & 1 & 0.7738 \\ 0.9035 & 0.9265 & 0.8524 & 0.7738 & 1 \end{bmatrix}$$

According to Equations(16)-(17), and in combination with the above matrix d , credibility measure $Crd(m_r)$ can be obtained as:

$$Crd(m_r)=[0.2083 \quad 0.2081 \quad 0.2039 \quad 0.1904 \quad 0.1893]$$

Finally, based on Equations(18)-(20), the basic probability matrix can be revised as:

$$U'' = \begin{bmatrix} I & II & III & IV & V & \Theta \\ 0.0879 & 0.0309 & 0 & 0 & 0 & 0.8812 \\ 0.1353 & 0 & 0 & 0 & 0 & 0.8648 \\ 0 & 0 & 0 & 0.0879 & 0.0005 & 0.9052 \\ 0 & 0.3225 & 0 & 0 & 0 & 0.7049 \\ 0.3753 & 0 & 0 & 0 & 0 & 0.6586 \end{bmatrix}$$

Based on the Equations (4)-(7), the final evaluation result, obtained by conducting $(m-1)$ syntheses of the revised evidence, is level IV.

Likely, the assessment results of seven cross sections are shown in Table 4.

Table 4 The predicting result of water quality

The serial number of cross section	The maximum synthetic probability	The suggested method	matter-element extension model	Actual investigation
1#	0.8326	I	II	I
2#	0.9212	I	II	I
3#	0.8862	I	II	I
4#	0.9035	II	II	II
5#	0.9285	I	I	I
6#	0.8162	I	I	I
7#	0.7892	I	I	I

The Evidence-Cloud theory is applied to evaluate the water quality. The assessment results are respectively depicted in Table 4. It can be found in Table 4 that the water quality levels from 1# to 7# cross sections are different. Except that the water quality level at 4# cross section is II; one at the rest cross section is I. It means that the water quality at 4# cross section is good, and ones at the rest cross sections are excellent. The

qualified rate of water quality in all cross sections arrives at 100%. So, for different cross sections, no any measurements should be taken to prevent the pollution of water quality.

According to the comparative results of the assessment model in Table 4, conclusions can be drawn that the results obtained by the suggested method are consistent with the actual investigation for seven different cross sections. Its accuracy reaches 100% for the proposed method, which is higher than the results from the matter-element extension model (80%) [27]. So, the conclusion demonstrates that it is feasible to estimate water quality using the suggested model. The method can provide more details for assessing water quality; for example, for 7# cross section, the magnitude of *DO* index is 2.39, which should belong to level V based on Table 1. In addition, the quality level of 5# cross section is more likely to be level I than that of the 6# cross section because the maximum synthetic probability(0.9285) of the 5# cross section for group I is higher than that of 6# cross section(0.8162). The results obtained using the suggested model accurately demonstrate the water quality grade and further determine the quality grade ranking for different cross sections at the same level.

(2) The analysis of sensitivity

The global sensitivity of each factor based on Equations (21) is calculated. The measurement results of the global sensitivity for the 5

influencing factors across different evaluation sections are shown in Figure 4.

From the above global sensitivity test results, it can be seen that the sensitivity of each evaluation factor to the water quality roughly exhibits two patterns: positive correlation and negative correlation. When the evaluation factors that exhibit a negative correlation increase, the water quality will decrease; when the evaluation factors that show a positive correlation improve, the water quality will also rise accordingly. The evaluation factor $X_1(\text{DO})$, $X_3(\text{TN})$, and $X_4(\text{TP})$ are the three most sensitive factors affecting the water quality. Therefore, they should be the focus of attention and control. Targeted measures, such as strengthening monitoring should be taken to ensure the stability of water quality.

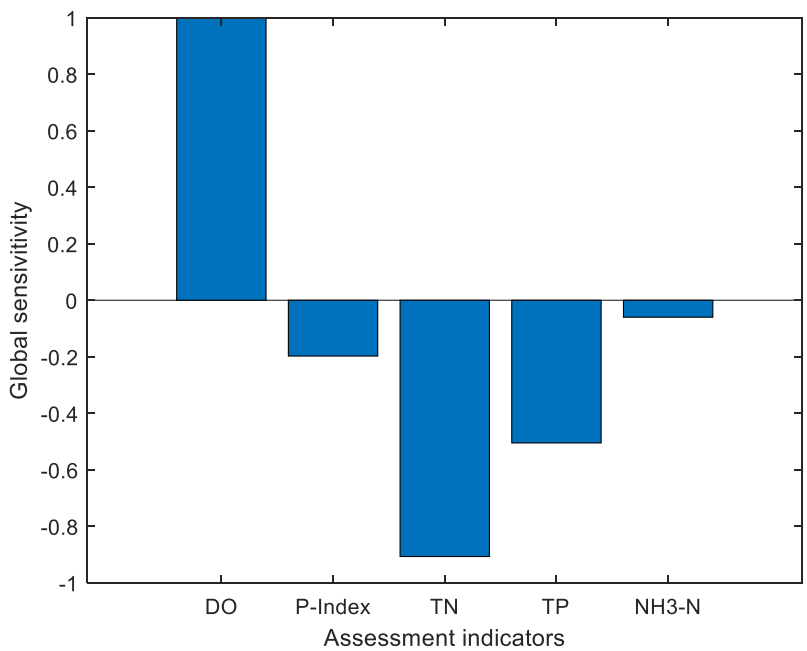


Figure 4. Test results of global sensitivity

Conclusions

321 Considering the DO (dissolved oxygen), permanganate index, TN
322 (total nitrogen), TP (total phosphorus) as well as $\text{NH}_3\text{-N}$, a new
323 evaluation method is introduced in this paper to assess the water quality
324 level based on the improved Evidence-cloud theory. The five different
325 evidence bodies are determined at first. Then, basic probability is
326 calculated. Finally, the synthetic probability of water quality is computed
327 using the evidence theory, and the water quality level is determined.

328 The proposed method is applied to assess the water quality level;
329 conclusions can be drawn that the results obtained by the suggested
330 method are consistent with the actual investigation for seven different
331 cross sections. Its accuracy reaches 100% for the proposed method, which
332 is higher than the results from the matter-element extension model (80%)
333 [27]. So, the conclusion demonstratthe water quality levels from 1# to 7#
334 cross sections are different. Except that the water quality level at 4# cross
335 section is II; one at the rest cross section is I. It means that the water
336 quality at 4# cross section is good, and ones at the rest cross sections are
337 excellent. The qualified rate of water quality in all cross sections arrives
338 at 100%. So, for different cross sections, no any measurements should be
339 taken to prevent the pollution of water quality.

340 The results of the practical application demonstrate that the water
341 quality is generally in a relatively stable state. Furthermore, based on
342 global sensitivity analysis, the sensitivity ranking of various influencing

factors is revealed, the evaluation factor $X_1(\text{DO})$, $X_3(\text{TN})$, and $X_4(\text{TP})$ are the three most sensitive factors affecting the water quality. Therefore, they should be the focus of attention and control. Targeted measures, such as strengthening monitoring should be taken to ensure the stability of water quality.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Funding Declaration

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