Post-Print of Surface Water Environmental Quality Assessment in Chengde Based on Improved Methods

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Abstract

To objectively reflect the water quality status of surface water, the fuzzy comprehensive evaluation method was improved using a combination of the Analytic Hierarchy Process and entropy weight method for weight assignment, along with the principle of weighted average comprehensive evaluation, and compared with the single-factor evaluation method, Nemerow index method, and traditional fuzzy comprehensive evaluation method to evaluate the surface water environmental quality in the Chengde area. The results show that: in 2021, the surface water quality in the Chengde area exhibited significant spatiotemporal variability; except for some monitoring sections during July–September where water quality was relatively poor, the water quality at the remaining sections was within Class I–III; the main factors affecting surface water quality in the Chengde area were CODMn and TP; the single-factor evaluation method and Nemerow index method cannot reflect the overall water quality status; compared with the traditional fuzzy comprehensive evaluation method, the improved fuzzy comprehensive evaluation method takes into account the interactions among various pollution factors, reduces the influence of individual water quality indicators on the evaluation results, and can rank water quality within the same category, making it more suitable for evaluating surface water environmental quality in the Chengde area.

Full Text

Evaluation of Surface Water Environmental Quality in Chengde Based on Improved Methods

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Abstract

To objectively reflect surface water quality conditions, this study improves the fuzzy comprehensive evaluation method by employing a combination of the Analytic Hierarchy Process (AHP) and entropy weight method for weight assignment, along with the weighted average comprehensive evaluation principle. The improved method was compared with single-factor evaluation, Nemerow index method, and traditional fuzzy comprehensive evaluation to assess the surface water environmental quality in the Chengde region during 2021. The results demonstrate significant spatiotemporal variations in surface water quality. Except for certain monitoring sections that exhibited poor water quality from July to September, water quality at all other sections fell within Classes I–III. The primary factors influencing surface water quality in Chengde were CODMn and NH3-N. Both single-factor evaluation and Nemerow index methods failed to reflect overall water quality status. Compared with traditional fuzzy comprehensive evaluation, the improved method accounts for interactions among various pollution factors while weakening the influence of individual water quality indicators on evaluation outcomes. Additionally, it enables ranking within the same water quality category, making it more suitable for evaluating surface water environmental quality in the Chengde region.

Keywords: water quality evaluation; improved fuzzy comprehensive evaluation method; analytic hierarchy process; entropy weight method; Chengde region

Introduction

Given the complexity of real-world water environmental quality and the inherent fuzziness in water quality classification and standard determination, fuzzy comprehensive evaluation methods have been widely applied in water quality assessment [1-3]. Compared with alternative approaches, fuzzy comprehensive evaluation can transform complex and uncertain information into fuzzy concepts, thereby quantifying qualitative problems and yielding more accurate evaluation results [4-5]. However, traditional fuzzy comprehensive evaluation employs an exceeding-standard weighting method that fails to reflect relationships among indicators or among evaluation objects, and is significantly influenced by the maximum pollution factor [6-7], leading to certain errors in evaluation results. Moreover, traditional fuzzy comprehensive evaluation determines water quality categories based on the maximum membership degree principle, which can result in information loss.

As a water conservation functional zone and ecological environment support area for the Beijing-Tianjin-Hebei region, Chengde has made substantial contributions to water resource security and aquatic ecological protection in this region for many years, attracting long-term and widespread attention to its water environmental quality. Water environmental quality evaluation forms the foundation for water resource development, utilization, and protection, and selecting appropriate water quality evaluation methods is prerequisite for objectively reflecting actual water environmental conditions [8]. Currently, commonly used water quality evaluation methods include single-factor evaluation [9-10], Nemerow index method [11-12], comprehensive water quality index method [13], fuzzy comprehensive evaluation [14-15], principal component analysis [16], grey clustering method, and artificial neural network models [17]. Considering that each method emphasizes different aspects and has certain limitations, comprehensive water quality assessment cannot be achieved using a single method alone. Therefore, this study improves the traditional fuzzy comprehensive evaluation method by modifying the weighting approach through combined weighting using AHP and entropy method, and replacing the maximum membership degree principle with the weighted average principle. This improved method was applied to evaluate the water environmental quality in Chengde, with results compared against those from single-factor evaluation, Nemerow index method, and traditional fuzzy comprehensive evaluation to examine the effectiveness of the improved approach.

1. Study Area Overview

Chengde City is located in northeastern Hebei Province, with geographical coordinates of 115°54 ~119°15 E, 40°11 ~42°40 N. The region exhibits decreasing precipitation from southeast to northwest. The city maintains a forest coverage rate of 55.8%, earning it the designation "Lungs of North China." As the source area of the Luan River, Chao River, Liao River, and Daling River, Chengde provides crucial water security for the Beijing-Tianjin-Hebei region. This study selected 12 national/provincial control monitoring sections—Dacaoping, Dasangyuan, Dazhangzi (II), Dazhangzi (I), Dangba, Dianzi, Tangsanying, Xinglongzhuang, Gubeikou, Guojiatun, Litai, and Mengguyingzi—as evaluation samples. Monthly water quality data from 2021 were collected, with CODMn and NH3-N as evaluation indicators. The spatial distribution of water quality monitoring sections is shown in [Figure 1: see original paper].

2. Methods

2.1 Single-Factor Evaluation Method The single-factor evaluation method [9] compares measured values at river sections with standard values from the *Environmental Quality Standards for Surface Water* (GB3838-2002) item by item, using the worst water quality category as the final evaluation result. This approach is heavily influenced by the maximum pollution factor.

2.2 Nemerow Index Method The Nemerow index method [11] is a water quality evaluation approach that comprehensively considers both the average and maximum values of standard indicators. It features simple calculation and can comprehensively and accurately reflect integrated water quality conditions. The calculation formulas are:

$$P_i = \sqrt{\frac{F_i^2 + F_{i\max}^2}{2}}$$

where C_i is the measured value of indicator i; S_{ij} is the standard value of indicator i for class j; F_i is the average value; $F_{i\max}$ is the maximum value; and P_i is the Nemerow pollution index for indicator i.

Based on standard concentrations of each evaluation indicator, the Nemerow pollution index corresponding to each water quality class was calculated. The Nemerow index grading standards are presented in .

2.3 Traditional Fuzzy Comprehensive Evaluation Method Traditional fuzzy comprehensive evaluation [14] offers clear results and systematic characteristics, enabling quantification of qualitative problems. It follows the maximum membership degree principle to evaluate comprehensive water quality categories, making it suitable for solving various nonlinear problems.

2.3.1 Establishment of Evaluation Sets The evaluation indicator set U was established as {CODMn, NH3-N}. According to the five water quality classes defined in GB3838-2002, the evaluation grade set V was established as {Class I, Class II, Class III, Class IV, Class V}.

2.3.2 Establishment of Membership Functions Membership functions [18] can take various forms including trapezoidal, rectangular, and normal distributions. The descending semi-trapezoidal distribution is commonly used in fuzzy comprehensive evaluation. Partial-large distribution functions apply to indicators where larger values indicate better water quality, while partial-small distribution functions apply to indicators where smaller values indicate better water quality. This study only involves partial-small distribution functions, calculated using formulas (3) through (6):

$$r_{ij} = \begin{cases} 1, & C_i \le S_{i,j} \\ \frac{S_{i,j+1} - C_i}{S_{i,j+1} - S_{i,j}}, & S_{i,j} < C_i < S_{i,j+1} \\ 0, & C_i \ge S_{i,j+1} \end{cases}$$

where C_i is the measured concentration of evaluation indicator i; $S_{i,j}$ is the standard value of indicator i for class j; and r_{ij} represents the membership degree of indicator i to class j standard values.

2.3.3 Weight Calculation Traditional fuzzy comprehensive evaluation typically employs the exceeding-standard weighting method, calculated as:

$$a_i = \frac{C_i}{\frac{1}{m}\sum_{j=1}^{m} S_{i,j}}$$

where a_i is the ratio of measured concentration to average standard value for indicator i; and W_i is the weight of indicator i.

2.3.4 Fuzzy Comprehensive Evaluation The weight matrix W is multiplied by the membership matrix R according to matrix operation rules to obtain the comprehensive evaluation matrix B, followed by final evaluation based on the maximum membership degree principle [19].

2.4 Improved Fuzzy Comprehensive Evaluation Method This study improves the traditional fuzzy comprehensive evaluation method in two key aspects: weighting method and evaluation principle.

2.4.1 Weighting Improvement The improved method adopts combined weighting using AHP and entropy weight method to weaken the influence of maximum pollution factors while considering interactions among indicators.

(1) AHP Weighting AHP [20] combines qualitative and quantitative analysis by decomposing evaluation indicators into a hierarchical structure, then conducting pairwise comparisons to construct a judgment matrix. The eigenvalues and eigenvectors are solved to obtain indicator weights, followed by consistency verification. The specific steps include: - Establishing the hierarchical structure with surface water environmental quality as the target layer, water quality classes as criteria layer, and evaluation indicators (CODMn, NH3-N) as scheme layer - Constructing the judgment matrix using measured concentration ratios between indicators to describe relative importance - Conducting consistency verification using online data analysis tools to calculate eigenvalues and eigenvectors, determining weights, and verifying that the consistency ratio $CR < 0.10$

(2) Entropy Weight Method The entropy weight method [21] determines objective weights based on indicator variability to eliminate human interference and improve accuracy. Calculation steps follow established methodologies.

(3) Combined Weighting AHP considers the impact of maximum pollution indicators through pairwise comparison but neglects inter-indicator relationships, while entropy weighting depends excessively on objective data and exhibits instability with sample variations. Therefore, this study adopts the average of AHP and entropy weights as the combined weight to balance both approaches.

2.4.2 Weighted Average Principle The maximum membership degree principle in traditional fuzzy comprehensive evaluation is replaced with the weighted average comprehensive evaluation principle to better preserve original information [22]. The weighted average principle is calculated as:

$$B_T = \sum_{j=1}^{k} j \cdot b_j^k$$

where b_j is the membership degree to class j water quality in the fuzzy comprehensive evaluation matrix; B_T is the evaluation result based on weighted average principle; and k is the weighting coefficient (taken as 1 in this study).

3. Evaluation Results

Based on monthly water quality monitoring data from Chengde surface water monitoring stations in 2021, 12 national/provincial control sections were evaluated using CODMn and NH3-N as indicators. Monthly monitoring results for all sections are shown in [Figure 2: see original paper].

3.1 Single-Factor Evaluation Results and Analysis Single-factor evaluation results are presented in [Figure 3: see original paper]. The results show significant spatiotemporal variations in water quality, with generally better quality during January-March and October-December. The poorest water quality occurred at Erdaohe Reservoir Inlet, Gubeikou, Guojiatun, Litai, Mengguyingzi, Shangbancheng Bridge, Tangsanying, and Xinglongzhuang sections, where the worst water quality in different months reached Class IV-V, with CODMn and NH3-N as the primary influencing factors. At Erdaohe Reservoir Inlet, CODMn concentrations peaked at 8.9 $mg \cdot L^{-1}$ and 0.38 $mg \cdot L^{-1}$ in July-September, respectively 1.78 times and 1.9 times the Class III standard limits. Guojiatun section showed the worst water quality, with CODMn ranging 7.1-7.5 $mg \cdot L^{-1}$ and NH3-N 0.12-0.18 $mg \cdot L^{-1}$. Litai section exceeded standards for CODMn during July-September, with maximum concentrations 1.64 times the Class III limit. Mengguyingzi section was significantly affected by CODMn, particularly in September when concentration reached 8.2 $mg \cdot L^{-1}$ (1.64 times the standard). Shangbancheng Bridge showed poorest quality in July-September with CODMn at 4.1-8.2 $mg \cdot L^{-1}$. Tangsanying section peaked in September with CODMn at 8.2 $mg \cdot L^{-1}$ and NH3-N at 0.18-0.29 $mg \cdot L^{-1}$. Xinglongzhuang section had poorest quality in July-September with CODMn at 7.9 $mg \cdot L^{-1}$ and NH3-N at 0.31 $mg \cdot L^{-1}$.

3.2 Nemerow Index Evaluation Results and Analysis Using formulas (1) and (2), Nemerow indices were calculated for all monitoring sections. Water quality categories were determined based on the Nemerow index grading standards in . Evaluation results are shown in [Figure 4: see original paper]. In 2021, water quality at all 12 national/provincial control sections in Chengde fell between Class I and Class III. The temporal distribution shows best quality during January-March and October-December, consistent with single-factor results.

Sections including Erdaohe Reservoir Inlet, Gubeikou, Guojiatun, Litai, Mengguyingzi, Shangbancheng Bridge, Tangsanying, and Xinglongzhuang reached Class IV-V during July-September. The proportions of Class I, II, and III water quality sections were 16.67%, 25.00%, and 50.00%, respectively.

3.3 Traditional Fuzzy Comprehensive Evaluation Results and Analysis Measured CODMn and NH3-N concentrations from 12 sections were substituted into formulas (3)-(6) to calculate membership matrices. Weights were determined using the exceeding-standard method, then multiplied with membership matrices to obtain water quality class membership degrees. Results following the maximum membership degree principle are shown in [Figure 5: see original paper]. Overall, Chengde' s surface water quality in 2021 showed spatiotemporal differences, with Class I-III water quality dominating. Sections Litai, Shangbancheng Bridge, and Xinglongzhuang showed notably poorer quality during July-September. Class I, II, and III water quality sections accounted for 8.33%, 33.33%, and 50.00%, respectively, with only 8.33% Class IV sections. The membership degrees to Class I-III water quality exceeded 0.5 for most sections, while membership to Class IV and below was zero for all sections. Starting from July, membership degrees to Class I-III began decreasing while Class IV membership increased, reaching a turning point in water quality deterioration. By October, membership to Class I-III increased again, returning to pre-July levels.

3.4 Improved Fuzzy Comprehensive Evaluation Results and Analysis Results from the improved fuzzy comprehensive evaluation method are presented in [Figure 6: see original paper]. Chengde' s surface water quality in 2021 fell between Class II and Class III. Temporally, water quality was poorest during July-September. Spatially, Erdaohe Reservoir Inlet, Gubeikou, Guojiatun, Litai, Mengguyingzi, Shangbancheng Bridge, Tangsanying, and Xinglongzhuang sections showed relatively poor quality. Except for Gubeikou (Class II), all other sections had B_T values between 2 and 3, indicating Class II-III water quality. The improved method enables ranking within the same water quality category. For Class III sections in July: Mengguyingzi > Dazhangzi (I) > Xinglongzhuang > Shangbancheng Bridge > Tangsanying > Litai > Guojiatun > Gubeikou. For Class III sections in August: Guojiatun > Tangsanying > Litai > Shangbancheng Bridge > Dazhangzi (I) > Xinglongzhuang > Erdaohe Reservoir Inlet. For Class III sections in September: Guojiatun > Tangsanying > Shangbancheng Bridge > Erdaohe Reservoir Inlet.

The improved method weakens the impact of maximum pollution factors, avoids information loss inherent in the maximum membership degree principle, and enables ranking within water quality categories, yielding results that more closely reflect actual water quality conditions.

3.5 Comparison of Four Evaluation Methods The proportions of various water quality classes from all four methods are compared in [Figure 7: see original paper]. Influenced by maximum pollution factors, single-factor evaluation and Nemerow index methods show significantly higher proportions of Class IV-V sections compared to traditional and improved fuzzy comprehensive evaluation methods. The improved fuzzy comprehensive evaluation method, by weakening maximum pollution factor influence while considering inter-indicator interactions, shows minimal Class IV section proportions and no Class V sections. This demonstrates that the improved method provides more reasonable and accurate evaluation results.

4. Conclusions

1) The improved fuzzy comprehensive evaluation method, combining AHP and entropy weight method, weakens the influence of maximum pollution factors while considering interactions among pollution factors. The weighted average comprehensive evaluation principle better preserves original information, making the improved method more suitable for surface water environmental quality evaluation.
2) In 2021, Chengde' s surface water quality showed significant spatiotemporal variations: temporally, July-September had the poorest water quality; spatially, Erdaohe Reservoir Inlet, Gubeikou, Guojiatun, Litai, Mengguyingzi, Shangbancheng Bridge, Tangsanying, and Xinglongzhuang sections had relatively poor quality, with CODMn and NH3-N as the main influencing factors.

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Note: Figure translations are in progress. See original paper for figures.