Postprint: Water Quality Assessment and Spatial Variation in Ningxia Yuehai Wetland

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Abstract

To further elucidate the influence of water depth, reed distribution, and the spatial distribution of inlets and outlets on the water quality of Yuehai Wetland in Ningxia, water samples were collected and analyzed at 14 sites across Yuehai Wetland during spring (May), summer (August), and autumn (November) of 2019 in accordance with the 'Surface Water Environmental Quality Standard (GB3838-2002)', and the spatial distribution characteristics of wetland water quality were evaluated using the fuzzy comprehensive evaluation method. The results indicated that: (1) The seasonal distribution characteristics of water quality indicators in Yuehai Lake showed that most parameters fell between Class III and Class IV water quality standards. Specifically, water quality was poorest in May, relatively better in November, and intermediate in August. (2) The spatial distribution characteristics of water quality indicators in Yuehai Lake were as follows: in May, water in shallow areas belonged to Class II, while water in reed areas, inlets, and deep water areas belonged to Class IV; in August, deep water areas and reed areas belonged to Class IV, the inlet belonged to Class I, and other areas belonged to Class III; in November, the inlet belonged to Class IV, while all other areas belonged to Class III. (3) The spatiotemporal variation of water quality indicators in Yuehai Lake was associated with external inputs such as tourism activities, artificial water replenishment, and bird habitat and reproduction, as well as natural and anthropogenic disturbances to lake sediments. The research findings provide valuable references for water resource management and ecological environment governance in Yuehai Wetland and other wetlands in arid regions.

Full Text

Water Quality Evaluation and Spatial Differentiation of Yuehai Wetland in Ningxia

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Abstract

To further investigate the influence of water depth, reed distribution, and the locations of water inlets and outlets on the water quality of Yuehai Wetland in Ningxia, water samples from 14 sampling points were collected and analyzed in May (spring), August (summer), and November (autumn) of 2019 according to the *Environmental Quality Standard for Surface Water (GB3838-2002)*. The spatial distribution characteristics of water quality were evaluated using the fuzzy comprehensive evaluation method. The results showed that: (1) Most seasonal water quality indicators of Yuehai Lake fell between Class III and Class IV standards, with the worst water quality in May, relatively good quality in November, and moderate quality in August. (2) The spatial distribution of water quality indicators exhibited distinct seasonal patterns. In May, the water body showed Class II quality in shallow areas, Class IV in reed zones, water inlets, and deep water areas. In August, deep water areas and reed zones exhibited Class IV quality, the water inlet showed Class I quality, and other areas showed Class III quality. In November, the water inlet showed Class IV quality, while other areas showed Class III quality. (3) The temporal and spatial variations of water quality indicators were related to external inputs such as artificial water supplementation, tourism activities, and bird habitat and reproduction, as well as natural and anthropogenic disturbances to lake sediments. These findings provide valuable references for water resource management and ecological environmental governance in arid region wetlands like Yuehai.

Keywords: Yuehai Wetland; water quality; fuzzy comprehensive evaluation; spatial difference; Ningxia

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Introduction

Wetlands represent a transitional zone between terrestrial and aquatic ecosystems and constitute a critical region for Earth sphere interactions. They are complex systems characterized by numerous uncertain factors and inherent fuzziness, making it difficult for single evaluation methods to comprehensively and quantitatively assess wetland water environments. Fuzzy mathematics can effectively address the impacts of ambiguous boundaries and monitoring errors on evaluation results. The fuzzy comprehensive evaluation method, based on fuzzy mathematics theory, uses membership functions to represent fuzzy states, classifies samples according to membership degrees, and determines water quality categories based on the maximum membership principle. Domestic researchers have conducted relevant studies using this approach. For instance, Yin Faneng et al. evaluated water quality in Daye Lake and found that total phosphorus and total nitrogen concentrations exceeded standards significantly, with overall water quality classified as Class IV. Zhou Ling et al. conducted a comprehensive evaluation of water quality across 20 sections of Hongze Lake, revealing that Class III water accounted for a large proportion. Chen Yu evaluated water quality at 8 sections of the Jiaoxi mainstream and found that all sections were Class III year-round. Wang Yufen et al. performed a fuzzy comprehensive evaluation of water quality in the Wanjiazhai Reservoir on the Yellow River, showing that both normal and low water periods were Class III. Ao Chenghuan et al. evaluated water quality in Baihua Lake, Guizhou Province, classifying it as Class III, with total phosphorus and total nitrogen identified as the main factors affecting water quality.

Yuehai Wetland was formed by connecting the original Xihu Lake located northwest of Yinchuan City through the "Returning Farmland to Wetland" program and the artificial Diannong Canal, which links it with other lakes and marshes in the basin and expands its depth, creating a nearly north-south oriented lake wetland. The lake experiences intense and diverse human activities along its course, with multiple interwoven point and non-point sources as well as external and internal pollutants, making the causes of water quality variation extremely complex. Previous research on Yuehai Wetland in Ningxia has been relatively limited. Bai Weidong et al. conducted continuous monitoring and analysis of Yuehai water quality from 2008 to 2010, revealing an annual pattern of moderate-heavy-moderate pollution across the lake surface. Zhong Yanxia et al. evaluated Yuehai water quality from 2009 to 2010 using the comprehensive pollution index method and analyzed the spatial distribution of ammonia nitrogen and CODcr pollutants using equal-distance weight interpolation, finding that pollution was most severe in spring with significant variation among sampling points, while autumn showed relatively lighter pollution with smaller differences between points. Li Shilong et al. assessed the health of Yuehai Wetland' s aquatic ecosystem in 2017, indicating an overall sub-healthy state. This study focuses on Yuehai Wetland, comprehensively considering different influencing factors such as lake depth, reed distribution, and the locations of water inlets and outlets, to thoroughly discuss the temporal and spatial distribution characteristics of lake water quality. Using the fuzzy comprehensive evaluation method for quantitative assessment, clear conclusions were obtained. The results provide valuable references for water resource management and ecological environmental governance in arid region wetlands like Yuehai.

1.1 Study Area Overview

Yuehai Wetland is located in Jinfeng District, Yinchuan City, only about 3 km from the city center, bordered by the Baolan Railway to the west and urban roads to the south. Its geographical coordinates are between 106°11′-106°14′E and 38°31′-38°37′N, with an elevation of approximately 1100 m. The total wetland area is 10 km^2, comprising 2.7 km^2 of lake area, 2.27 km^2 of marsh wetland, 1.79 km^2 of constructed wetland, 0.38 km^2 of fish ponds, and 0.09 km^2 of other areas. During the high-water period, the average depth reaches 2.7 m. The wetland has relatively abundant water resources, complete aquatic vegetation, and relatively intact biodiversity, serving as an important habitat and transit station for bird migration in China' s arid regions and playing a significant role in protecting urban biodiversity and improving the ecological environment. Geomorphologically, Yuehai is situated in the alluvial-lacustrine plain in front of the Helan Mountains, within the main body of the Yellow River irrigation area, where the land is fertile and agriculture is well-developed. Different regions have different crop types, irrigation methods, and groundwater recharge conditions and dynamic changes. As an urban wetland, Yuehai plays an important role in ecological landscape creation, environmental improvement, and wetland tourism, becoming a critical node for maintaining the stability of the Yinchuan Plain oasis with significant ecological importance. Water quality is a crucial factor affecting wetland ecological quality. Since Yuehai is connected to other lakes and marshes in the basin through the artificial Diannong Canal, its attribute as an independent lake has changed, resulting in a relatively long flow path with diverse habitats and human activities along the way. The interweaving of point and non-point sources as well as external and internal pollutants makes the causes of water quality variation complex and diverse.

1.2 Sampling Design and Sample Collection

1.2.1 Sampling Site Setup and Sample Collection Based on remote sensing imagery, Google Earth maps, and field investigations, and considering factors such as surrounding non-point and point source pollution, spatial distance, and vegetation distribution, 14 data collection points were established in Yuehai Wetland from south to north along the water supplement inlet to the drainage outlet, according to the distribution of vegetation and islands within the wetland. The coordinates of each collection point were recorded to ensure consistency with subsequent sampling points. Sampling was conducted seasonally in May (spring), August (summer), and November (autumn). Sampling point locations are shown in Figure 1. Water samples were collected at 50 cm below the water surface using a water sampler, placed in polyethylene bottles, protected from light, and immediately brought back to the laboratory for storage in a refrigerator at 4°C. After collection, water quality indicator concentrations were measured promptly. Indoor water sample measurement indicators included NH_3-N, total nitrogen, total phosphorus, CODMn, total organic carbon, and suspended solids. For the suspended solids indicator, some water samples needed to be filtered through a 0.45 m membrane before measurement. Field measurements included water temperature, transparency, depth, pH, conductivity, dissolved oxygen, and total dissolved solids. Information for each sampling point is provided in Table 1.

1.2.2 Sample Processing and Testing Methods After retrieval, samples were analyzed for concentrations of total phosphorus, total nitrogen, NH_3-N, CODMn, total organic carbon, and suspended solids. Total phosphorus was measured using the ammonium molybdate spectrophotometry method; total nitrogen using the alkaline potassium persulfate digestion UV spectrophotometry method; NH_3-N using the Nessler' s reagent spectrophotometry method; CODMn using the potassium permanganate titration method; total organic carbon measured with a total organic carbon analyzer; and suspended solids determined using the gravimetric method.

1.3 Research Methods

The fuzzy comprehensive evaluation method was employed for Yuehai water quality assessment.

1) **Establishment of Factor Set**: Based on established principles and measured data, evaluation indicators were selected to create an evaluation factor set. According to Yuehai Wetland' s water quality, six water quality indicators were selected. The evaluation factor set was denoted as {NH_3-N, total nitrogen, total phosphorus, CODMn, total organic carbon, suspended solids}.

2) **Establishment of Evaluation Grades**: According to the *Environmental Quality Standard for Surface Water (GB3838-2002)*, five grade standards were established: Class I, Class II, Class III, Class IV, and Class V.

3) **Establishment of Fuzzy Relation Matrix**: The fuzzy relation matrix included six evaluation indicators and five grade standards, forming a 6$×$5 single-factor membership fuzzy matrix function.

4) **Determination of Membership Vectors**: Membership function formulas were established corresponding to five levels for minimal-type indicators. For Class I water quality (j=1), when c ≤ s 1, the membership function is:

$$\gamma_{ij} = \begin{cases} 1 & \text{if } c_i \leq s_{i1} \\ \frac{s_{i2}-c_i}{s_{i2}-s_{i1}} & \text{if } s_{i1} < c_i \leq s_{i2} \\ 0 & \text{if } c_i > s_{i2} \end{cases}$$

For intermediate water quality grades (j=2,3,4), the membership function is:

$$\gamma_{ij} = \begin{cases} 0 & \text{if } c_i \leq s_{i(j-1)} \text{ or } c_i > s_{i(j+1)} \\ \frac{c_i - s_{i(j-1)}}{s_{ij} - s_{i(j-1)}} & \text{if } s_{i(j-1)} < c_i \leq s_{ij} \\ \frac{s_{i(j+1)} - c_i}{s_{i(j+1)} - s_{ij}} & \text{if } s_{ij} < c_i \leq s_{i(j+1)} \end{cases}$$

For the worst grade (j=5), when c > s $_4$, the membership function is:

$$\gamma_{ij} = \begin{cases} 0 & \text{if } c_i \leq s_{i4} \\ \frac{c_i - s_{i4}}{s_{i5} - s_{i4}} & \text{if } s_{i4} < c_i \leq s_{i5} \\ 1 & \text{if } c_i > s_{i5} \end{cases}$$

where c is the measured value of the evaluation factor and s is the standard value for the j-th water quality class.

5) **Establishment of Fuzzy Comprehensive Evaluation Matrix**: Based on the membership functions, the fuzzy matrix Y was determined.

6) **Establishment of Fuzzy Weight Coefficient Set**: The formula is:

$$\omega_i = \frac{c_i}{\bar{s}_i}$$

where c is the measured value of the evaluation factor and s̄ is the average of the five class standards for that factor. To perform fuzzy operations, the weights ω must be normalized to the interval [0,1], so the weight set A was normalized as:

$$A_i = \frac{\omega_i}{\sum_{i=1}^{n} \omega_i}$$

Based on these formulas, the weight sets for each monitoring point were calculated.

7) **Determination of Comprehensive Evaluation Grade**: Finally, the comprehensive evaluation grade was determined based on the matrix values.

2.1 Seasonal Distribution Characteristics

As shown in Figure 2, water quality indicators including NH_3-N, total nitrogen, total phosphorus, CODMn, and suspended solids in Yuehai Lake exhibited distinct seasonal distribution patterns. NH_3-N concentrations were highest at all sampling points in May, reaching 1.08 $mg \cdot L^{-1}$ and 1.01 $mg \cdot L^{-1}$ at points 1 and 2 respectively, with an average of 0.11 $mg \cdot L^{-1}$. Concentrations were lowest in November, with an average of 0.03 $mg \cdot L^{-1}$. Total nitrogen showed significant seasonal variation, with the highest values in May (average 0.66 $mg \cdot L^{-1}$) and the lowest in November (average 0.03 $mg \cdot L^{-1}$). Total phosphorus showed even more pronounced seasonal differences, with May concentrations exceeding 0.5 mg · L^{-1} at points 1, 2, 3, and 5, including some shallow areas, drainage outlets, and reed zones. Dissolved oxygen, a critical factor ensuring aquatic organism survival and maintaining ecological balance, also showed clear seasonal variation, with the lowest average value of 2.25 mg · L^{-1} in May. CODMn, an important indicator reflecting the severity of pollution, exhibited different seasonal trends, with overall concentrations ranging from 6.56–9.22 mg · L^{-1}. Maximum values appeared in May, reaching 9.22 mg · L^{-1} in reed zones. As a comprehensive indicator of total organic matter content in water, CODMn accurately reflects overall organic pollution status and serves as an important reference for evaluating organic contamination. Suspended solids, the primary cause of lake turbidity and an important index for water pollution assessment, showed average concentrations of 32.14 mg · L^{-1} in May, 50.67 mg · L^{-1} in August, and 53.61 mg · L^{-1} in November. Overall, different water quality indicators and even the same indicator showed significant variations across different seasons and within the same season.

2.2.1 Determination of Membership Functions

Using formula (1) to establish the comprehensive membership matrix Y, a trapezoidal distribution was adopted to determine membership functions. Taking sampling point 1 in May as an example, the calculated membership function matrix is:

$$Y = \begin{bmatrix} 0.180 & 0.820 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & 0.000 & 1.000 \\ 0.000 & 0.000 & 0.000 & 0.000 & 1.000 \\ 0.000 & 0.000 & 0.000 & 0.000 & 1.000 \\ 0.000 & 0.000 & 0.000 & 0.000 & 1.000 \\ 0.000 & 0.000 & 0.000 & 0.000 & 1.000 \end{bmatrix}$$

Similarly, membership functions for other sampling points across three months were calculated.

2.2.2 Monthly Water Quality Indicator Weights

Weight coefficients for each indicator were calculated and normalized. The results are shown in Tables 2-4. Exceedances of total phosphorus, total nitrogen, and CODMn were the main causes of water quality deterioration and eutrophication in Yuehai Lake, with total phosphorus and total nitrogen primarily originating from industrial wastewater, domestic sewage, and fertilizers.

2.2.3 Fuzzy Matrix Composite Operation

According to the fuzzy water quality model, by substituting the weight set A and fuzzy relation matrix Y into the calculation, the fuzzy comprehensive evaluation set B was obtained. For sampling point 1 in May:

$$B = A \circ Y = [0.180 \quad 0.200 \quad 0.321 \quad 0.299 \quad 0.000]$$

Similarly, fuzzy comprehensive evaluation sets for all monitoring points across three months were calculated. The evaluation sets for 14 points were compiled to obtain the fuzzy comprehensive evaluation results for May, August, and November. In May, water quality categories at more than half of the sampling points were Class IV, including the shallow area (point 1), drainage outlet (point 2), deep water area (point 3), and reed zone (point 8). In August, more than half of the sampling points were Class III, with deep water areas (points 3 and 4) and reed zones (points 8 and 9) classified as Class IV, while the water inlet (point 14) was Class I and other areas were Class III. In November, more than half of the sampling points were Class III, with the water inlet (point 14) classified as Class IV and other areas as Class III.

2.3 Spatial Differentiation Characteristics of Yuehai Water Quality

Through spatial interpolation of the fuzzy comprehensive evaluation results (Figure 3), distinct spatial differences in water quality categories were observed across seasons. In May, Yuehai water exhibited Class II quality in shallow areas and Class IV in reed zones, water inlets, and deep water areas. In August, deep water areas and reed zones showed Class IV quality, the water inlet showed Class I quality, and other areas showed Class III quality. In November, the water inlet showed Class IV quality while other areas showed Class III quality. The poor water quality in reed zones in May may be attributed to their role as bird breeding habitats with high external pollutant inputs. The better water quality at the inlet in August resulted from minimal external input due to absence of artificial water supplementation. The poor water quality at the inlet in November was due to concentrated water supplementation activities and external inputs.

3 Discussion

3.1 Analysis of Seasonal Distribution Characteristics

Most water quality indicators in Yuehai ranged between Class III and Class IV standards, showing significant seasonal variation. Indicators were relatively highest in May, likely because emergent plants and phytoplankton were in their germination stage and had not yet consumed nutrients. Additionally, a large-scale concentrated water supplementation activity was conducted in early May, introducing external pollutants. Spring winds also disturbed sediments, suspending pollutants and affecting water quality, as evidenced by higher suspended solids in May compared to other months. August indicators were higher than November but lower than May, with average CODMn values of 7.54 $\text{mg} \cdot \text{L}^{-1}$ and total nitrogen averages of 0.04 $\text{mg} \cdot \text{L}^{-1}$, both lower than May values

(7.83 $mg \cdot L^{-1}$ and 0.91 $mg \cdot L^{-1}$ respectively). This may be because August represents the peak growth period for aquatic plants, which absorbed nutrients and purified water quality. However, August is also the tourism peak season, with increased pollutant inputs from tourism activities affecting water quality. November showed the lowest overall indicators and relatively good water quality. Although artificial supplementation occurred in autumn, smaller wind waves caused less sediment disturbance.

3.2 Analysis of Spatial Differentiation Characteristics

In May, Yuehai water showed Class II quality in shallow areas and Class IV in reed zones, water inlets, and deep water areas. Reed zones are also bird breeding habitats with high external pollutant inputs, and reed adsorption capacity had not yet developed, leading to high pollutant concentrations. The relatively poor water quality at the inlet may be due to both poor-quality supplement water and frequent human activities near the urban area causing pollutant inputs. Deep water areas are open for tourism, with the Green Expo Park on the east bank and Yuehai amusement park on the west bank, both involving water-based tourism projects. Human activity inputs and sediment disturbance contribute to deteriorating water quality in these areas.

In August, deep water areas and reed zones showed Class IV quality, the water inlet showed Class I quality, and other areas showed Class III quality. August represents the tourism peak season with numerous visitors, and external inputs from human activities and Green Expo Park runoff pollutants could degrade water quality in these areas. Although reeds grew rapidly with obvious adsorption effects, this was insufficient to offset pollution from bird breeding.

In November, deep water areas and reed zones showed Class III quality, other areas showed Class III quality, and the water inlet showed Class IV quality. Although water supplementation occurred in November, autumn winds were small with minimal sediment disturbance. November is the off-season for tourism with fewer human activities, reduced external inputs, and less sediment disturbance, resulting in lower regional pollutant indicators.

4 Conclusions

1) Analysis of seasonal distribution characteristics revealed that most water quality indicators in Yuehai Lake ranged between Class III and Class IV standards, showing significant seasonal variation. Indicators were highest in May and lowest in November, reflecting seasonal patterns.

2) Spatial distribution analysis showed that in May, Yuehai water exhibited Class II quality in shallow areas and Class IV in reed zones, water inlets, and deep water areas. In August, deep water areas and reed zones showed Class IV quality, the water inlet showed Class I quality, and other areas showed Class III quality. In November, the water inlet showed Class IV quality while other areas showed Class III quality.

3) The temporal and spatial variations of water quality indicators were related to external inputs from artificial water supplementation, tourism activities, and bird habitat and reproduction, as well as natural and anthropogenic disturbances to lake sediments.

4) Due to experimental limitations, supplement water and sediment pollutants were not monitored. Future research should collect supplement water and sediment pollutant data to deepen understanding of their impacts on Yuehai water quality.

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