ANALYSIS OF THE COUPLING BETWEEN WATER QUALITY AND AQUATIC COMMUNITIES AND ECOLOGICAL THRESHOLDS AT THE BASIN SCALE IN CHINA

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Abstract. The Yangtze River Basin in China is chosen as the study region to investigate the interaction of watersheds and ecological thresholds. This study used 120 sampling points and applied a combination of descriptive statistics, correlation analysis, regression analysis, and ecological threshold analysis to investigate water quality and aquatic organisms at different locations. It was found that dissolved oxygen (DO) is positively correlated with the quantity of phytoplankton (correlation coefficient 0.45, $P < 0.01$), while ammonia nitrogen shows a significant negative correlation (e.g., COD is -0.42, $P < 0.01$). The established multivariate linear regression model explained 68-72% of the variation in the characteristic parameters of aquatic communities. The ecological threshold of ammonia nitrogen affecting the number of plankton species is 0.8 mg/L. Once this critical value was exceeded, the number of plankton decreased sharply. The research results can provide a scientific basis for protecting and managing the ecological environment of the basin.
Keywords. *ecological interaction; environmental factor; biological indicator; statistical modeling; China*

Introduction

The watershed ecosystem is the most complex and fundamental ecological unit on Earth, playing an essential role in maintaining water supply, maintaining biodiversity, and regulating climate. The state of water quality in the water body is closely related to the structure of its biological community, and they interact to form a dynamic ecosystem. In-depth research on the coupling between the water environment and the aquatic community in small watersheds, along with its ecological threshold, has important theoretical and practical significance for understanding the functioning of the watershed ecosystem, ensuring its healthy and sustainable development, and guiding the governance of the ecological environment.

Due to the effects of climate change and human activities, river basin ecosystems are confronted with unprecedented serious challenges (Savita and Dwivedi, 2024). With the acceleration of urbanization and industrialization, agricultural non-point source pollution has become increasingly severe, and many pollutants have been discharged into the watershed, causing environmental problems such as water environment deterioration and eutrophication (Ramovha et al., 2024). Heavy metals and organic pollutants in industrial waste water, excessive application of fertilizers and pesticides in agriculture, and nitrogen, phosphorus, etc. have not only altered the chemistry of water, but also endangered the

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survival, reproduction and growth of aquatic organisms (Stieger and Mckenzie, 2024). The deterioration of the water environment may cause habitat destruction and reduced species diversity, and even lead to the extinction of some sensitive species; at the same time, changes in the structure of biological communities in water bodies in turn affect the water quality of water bodies, and through biological metabolism, material circulation and other processes, thus affecting the self-purification and ecological functions of water bodies (Zhi et al., 2023). This complex interaction between the water environment and aquatic organisms makes the balance of the basin ecosystem more fragile. Once a certain threshold is exceeded, it will lead to ecosystem degradation or even collapse.

In recent years, domestic and foreign scholars have researched the relationship between aquatic communities and water quality (Castro and Obusan, 2023). Existing studies have focused on the impact of a single water quality indicator on specific aquatic organisms. Combining indoor experiments with field surveys revealed the toxic effects and physiological and biochemical effects of some pollutants on aquatic organisms (Yazman et al., 2024). Some scholars intend to use multidisciplinary theories and methods, such as community ecology and ecotoxicology, to analyze aquatic communities' composition, diversity, and ecological niche under different water quality conditions. Recently, with the introduction of ecosystem theory and system science, people have started to study the interaction between aquatic environment and aquatic community from the view of ecosystem. However, the current research still lacks (Liu et al., 2022). Existing researches are mainly limited to small scale, lack systematic study about the relationship between water environment and biological community, and do not fully reflect the integrity and complexity of basins. However, the current research on the ecological threshold of the coupling relationship between water environment and aquatic communities is relatively weak, and the environmental threshold is an essential indicator for measuring the changes in the state of the ecosystem, which is of great significance to the management and protection of the basin ecological environment (Yin et al., 2024). The shortcomings of existing research have restricted the in-depth understanding and effective regulation of the evolutionary laws of the basin ecosystem.

The ecological threshold is an essential concept of ecosystem ecology. It refers to the ability of an ecosystem to maintain a relatively stable state after being disturbed by the outside world (Alahmed et al., 2022). It is very important to accurately identify the ecological threshold of water environment coupled with water community, so as to draw up scientific water environmental management policies and measures. For example, identifying the significant impact of key water quality indicators (nitrogen, phosphorus, etc.) on the structure and function of aquatic communities can provide a basis for formulating basin pollutant emission standards and implementing ecological restoration projects to avoid excessive degradation and destruction of ecosystems. The research and implementation of environmental thresholds will help to deeply understand the stability and resilience of ecosystems and provide theoretical support for responding to global climate change and human activity disturbances.

This project intends to take the Yangtze River Basin in China as the research object, systematically analyze the coupling relationship between water environment and aquatic communities, and use mathematical statistics methods to determine its ecological threshold (Mânica and de Lima Isaac, 2023). The internal relations of water environmental factors and the characteristic parameters of water community are analyzed by means of statistics, correlation analysis and regression analysis. This paper establishes the coupling relationship between water quality and water community. Then, by using the advanced

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ecological threshold analysis method, the threshold value of the water environment is precisely recognized, and the evolution rule and the critical node are revealed. This project can not only enrich the knowledge of the relationship between the water environment and the water community, but also provide the scientific foundation and decision support for the conservation and management of the river basin. The objective of this study is to clarify the coupling mechanism between water quality and aquatic communities in the Yangtze River Basin, determine the ecological thresholds of key water quality indicators, and provide a scientific basis for basin ecological management.

Overview of the research area

This project takes the Yangtze River Basin in China, located at 90°33'-122°25' east longitude and 24°30'-35°45' north latitude, as the research area, with a basin area of about 1.8 million km^2. From the perspective of topography and landform, the basin comprises plateaus, mountains, hills, and plains, with high elevations in the west and low elevations in the east and diverse landform types (Chapman et al., 2023). In the upper reaches of the Qinghai-Tibet Plateau and Hengduan Mountains, there are great undulating terrain and obvious drop in the river, especially in the Jinsha River Basin. It has become an important water source in the region; the middle reaches are mountainous, with gentle terrain and winding rivers. The lower reaches of the Yangtze River are characterized by flat and open terrain, dense river network, mild water flow, high population density and economic development.

From the climatic point of view, it is a subtropical monsoon climate belt, with high temperature and heavy rainfall in summer, an average annual temperature of 16 to 18℃, and annual precipitation of 800~1600 mm (Chinese Meteorological Administration, 2023). The temporal and spatial distribution of rainfall is not uniform. It is mainly concentrated from May to September. In the rainy season, a large amount of surface runoff carries a large amount of sediment, agricultural non-point source pollutants and surface pollutants into the river, which easily leads to turbidity of water bodies and increased concentrations of contaminants such as nitrogen and phosphorus (Trebitz and Wulfhorst, 2021).

The basin has a developed water system, with the Yangtze River as the main trunk running across the east and west, forming a vast and complex water system network. These rivers not only provide essential water resources for agricultural irrigation, industrial production, and residents' lives in the surrounding areas, but also are essential habitats for rare aquatic organisms such as Acipenser sinensis (Chinese sturgeon) and Lipotes vexillifer (Yangtze River dolphin), as well as habitats for many fish and zooplankton (Singh et al., 2021). However, along with the rapid development of industrialization and urbanization, the river system is being disturbed day by day. There are some rivers shrinking, eutrophic, and polluted by heavy metals, which threaten the health of the river basin.

Data collection

Collecting water samples

According to scientific and standardized principles, there are 120 sampling points. One sampling point is set for every 100-200 km of the Yangtze River mainstream, considering factors such as the characteristics of the basin water system, the intensity of human activities, and ecologically sensitive areas (Chawla et al., 2024). This project plans to set up monitoring points in key areas such as the confluence of main tributaries and main and

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tributary rivers, 5-10 km downstream of large urban sewage treatment plants, typical agricultural river sections, and national nature reserves.

This project was conducted from January 2022 to December 2023, adopting a sampling frequency of once a month. Sampling was intensified to once every two months from May to September (rainy season), and maintained once a month during the dry season (December to February). The number of water samples collected each month followed a consistent pattern, with adjustments for intensified sampling during the rainy season.

Divide 5 L of water samples at each sampling point into three clean polyethylene sampling bottles. A portable multiparameter water quality analyzer (Model: YSI ProPlus, manufactured by YSI Inc., Yellow Springs, OH, USA) is used to measure the physical and chemical parameters of water quality, such as water temperature, pH, Dissolved oxygen (DO) and electrical conductivity. The standard analytical method is used to measure chemical oxygen demand (COD), Ammonia nitrogen (NH_3-N), Total phosphorus (TP), and Total nitrogen (TN).

Sample collection

The collection of aquatic biological samples mainly includes plankton, benthic animals, fish, etc. This project intends to use a 20 μm aperture plankton net (manufactured by Hydro-Bios, Kiel, Germany) and two methods to collect it: horizontal trawl (tow distance 50 m) and vertical trawl (from bottom to water surface), fix it with 5% formaldehyde solution, and count its species and quantity using an optical microscope (Model: Olympus CX43, manufactured by Olympus Corporation, Tokyo, Japan).

This project intends to use a Peterson mud meter (manufactured by Wildco, Yulee, FL, USA) to collect benthic animal samples, three samples per sampling point, and screen out benthic animals through 40 mesh sieves. After fixation with 75% ethanol, their species will be identified according to relevant classification monographs (e.g., “Freshwater Benthic Invertebrates of China” by Wang et al., 2015; “Taxonomy of Aquatic Insects” by Zhang et al., 2018), and their biomass and density will be calculated.

Sampling will be carried out using fishing gear such as gill nets (the mesh size can be adjusted according to the size of fish in different river sections) and ground cages. Electric fishing (using Model: Smith-Root LR-24, manufactured by Smith-Root Inc., Vancouver, WA, USA) will be implemented in some areas without damaging the ecological environment and complying with fishery regulations (limited to the scope of scientific research permission). This project intends to collect fish, identify their species according to “Fishes of the Yangtze River Basin” by Chen et al. (2020), measure their biological indicators such as body length and weight, record their gonad development, and store them at -80°C refrigerator (Model: Thermo Scientific Revco ULT freezer, manufactured by Thermo Fisher Scientific, Waltham, MA, USA) for laboratory testing.

Materials and methods

Analysis of water environment quality status

The laboratory uses the potassium dichromate (PD) reflux digestion-titration method to determine COD. PD is used to oxidize the reducing substances in the water, ferroin is used as an indicator, and the residual PD is titrated with ammonium ferrous sulfate standard solution (Doka et al., 2022). The COD value is calculated according to the dosage, thereby reflecting the total organic matter content in the water; the Nessler reagent method is used to determine NH_3-N. The Nessler reagent and ammonia-nitrogen react to form a brown compound, and the concentration of ammonia-nitrogen is measured at 420 nm using a spectrophotometer (Model: Shimadzu UV-1800, manufactured by Shimadzu Corporation, Kyoto, Japan). The total phosphorus was determined by ammonium molybdate spectrophotometry. The phosphorus content in the water was digested with potassium persulfate, then reacted with ammonium molybdate to form phosphomolybdic heteropoly acid. Ascorbic acid was reduced to create a blue complex, and the TP content was determined by 700 nm colorimetry using the same spectrophotometer. The TN was determined by alkaline potassium persulfate digestion. At 120-124℃, nitrate was oxidized by alkaline potassium persulfate, and the TN concentration was calculated at 220 nm and 275 nm using the spectrophotometer.

Analysis of aquatic biological communities

Biological diversity indicators, for example, Shannon wiener Diversity Index $\left(\left(H' = -\sum_{i-1}^{S} p_i \ln\ p_i, p_i\right.\right.$ is the ratio of the population of i species to the total population, and S is the species count), Simpson Dominant Index $\left(D = 1 - \sum_{i-1}^{S} p_i^2\right)$ and Pielou Evenness Index $J = \frac{H'}{\ln\ S}$.

Descriptive statistical analysis

Mean, standard deviation and variance are used to describe the features of water bodies and aquatic organisms. Water quality in the whole basin can be obtained by computing the mean of water quality index. The standard deviation is used to reflect the spatial volatility of water quality indicators; the coefficient of variation method is used to eliminate the dimensional effect and compare the discreteness of different water quality indicators.

Correlation analysis

The linear and nonlinear relationships between different water quality indicators and water biological community characteristic parameters are studied using the Pearson and Spearman rank correlation coefficients. Pearson correlation analysis is performed on continuous variables that conform to the normal distribution (such as some water quality indices and biomass). Spearman Rank Correlation Coefficient was used to analyze the non-normal distribution or hierarchical data (e.g., species richness ranking) to determine the monotonic correlation among the variables, and to select water quality indicators with significant influence on the community.

Regression analysis

Significant water quality indicators were selected as independent variables, characteristic parameters of aquatic communities were chosen as dependent variables, and linear and multivariate linear regression models were established. The least squares method was used to fit the regression equation to determine the coefficient of influence of the independent variable on the explanatory variable (Atazadeh et al., 2024). The regression coefficients were calculated by minimizing the sum of squared residuals between the observed and predicted values.

To validate the model's effectiveness across different water body types, we divided the sampling points into categories: small mountain rivers (high elevation), large rivers, reservoirs, and lakes. The model was applied to each category, and the adjusted R^2 values for each subset were calculated, with results showing adjusted R^2 ranging from 0.62 to 0.75, indicating good performance across different water body types.

Ecological threshold method

The ecological threshold was determined by using quantile regression, breakpoint regression, and change-point analysis. The effects of different quantile parameters (0.25, 0.5, 0.75) on the characteristic parameters of water community were investigated by quantile regression. Breakpoint regression determines the specific location of the ecological threshold by identifying the critical point where the change of water quality indicators leads to a sudden change in the characteristics of aquatic communities (Atazadeh et al., 2021). Change-point analysis was used to confirm the identified breakpoints by analyzing the likelihood ratio of the data before and after potential threshold values. Combined with the Bootstrap resampling method (1000 repeated samplings), the threshold was estimated, and the significance test was performed to improve the accuracy and reliability of threshold determination.

Spatial and temporal variability analysis

The spatial heterogeneity of water quality parameters was analyzed using Kriging interpolation in ArcGIS (Version 10.8, ESRI Inc., Redlands, CA, USA) to generate spatial distribution maps. Temporal variability was assessed by comparing monthly and seasonal means, and analyzing the coefficient of variation across different time periods.

Results and analysis

Descriptive statistical results of water quality and aquatic biological communities

Descriptive statistical analysis was performed on the water quality and aquatic biological community data of 120 sampling points in the Yangtze River Basin. The results are shown in *Table 1*.

Table 1. *Descriptive statistical results*

Indicator type	Index name	Mean	SD	Min	Max	Cov
Water quality indicators	Water temperature (°C)	18.5	3.2	8.2	28.7	0.17
	pH value	7.3	0.4	6.1	8.5	0.05
	DO (mg/L)	6.8	1.5	3.2	9.8	0.22
	COD (mg/L)	25.6	6.3	12.1	45.2	0.25
	NH_3-N (mg/L)	1.2	0.5	0.1	3.8	0.42
	TP (mg/L)	0.18	0.06	0.05	0.35	0.33
	TN (mg/L)	2.5	0.8	1.0	5.2	0.32
Aquatic community indicators	Number of plankton species	25.3	8.7	12	45	0.34
	Biomass of plankton (mg/L)	15.6	4.8	6.2	28.9	0.31
	Number of benthic animal species	12.7	4.3	5	22	0.34
	Biomass of benthic animal (g/m²)	35.8	12.6	10.5	68.2	0.35
	Number of fish species	18.6	6.1	8	32	0.33
	Biomass of fish (kg/100 m²)	45.2	15.7	18.3	82.5	0.35

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In terms of water quality index, water temperature variability is small, reflecting that the change of water temperature in the basin is relatively stable; however, the coefficient of variation of NH_3-N is the highest, reaching 0.42, indicating that there are noticeable spatial differences in NH_3-N concentration in the basin, which may be due to differences in the intensity of human activities (such as industrial emissions, agricultural fertilization and domestic sewage). Temporally, NH_3-N concentrations peak in June-August (rainy season) due to non-point source pollution runoff. In the aquatic community index, the coefficient of variation of benthic animals and fish biomass is 0.35, reflecting the uneven distribution of biomass between different points, which may be affected by multiple factors such as water quality and habitat.

Correlation analysis results between water quality and aquatic community

The Pearson correlation coefficient and Spearman rank correlation coefficient were used to conduct correlation analysis on water quality indicators and characteristic parameters of aquatic community, and significant correlations were screened out ($P < 0.05$). The results are summarized in *Table 2*.

Table 2. *Correlation analysis results*

Water quality indicators	Plankton species (n)	Plankton biomass	Benthic animal species (n)	Benthic animal biomass	Fish species (n)	Fish biomass
Water temperature	0.32*	0.28*	-0.15	0.12	0.25*	0.30*
pH	0.18	0.22*	0.21*	0.23*	0.16	0.19
DO	0.45**	-0.31*	0.38**	-0.25*	0.42**	-0.33*
COD	-0.35*	-0.41**	-0.28*	-0.36*	-0.32*	-0.38*
NH_3-N	-0.42**	-0.48**	-0.35*	-0.43**	-0.38*	-0.45**
TP	0.29*	0.33*	0.26*	0.28*	0.24*	0.27*
TN	0.31*	0.35*	0.27*	0.30*	0.26*	0.29*

*P < 0.05, **P < 0.01

As shown in *Table 2,* DO is significantly positively correlated with the number of plankton species, benthic animal species, and fish species, and significantly negatively correlated with the biomass of plankton, benthic animals, and fish, indicating that the increase of DO in the water body is conducive to the rise of aquatic species. In contrast, excessive DO will inhibit the accumulation of biomass. Water temperature shows positive correlations with plankton species, plankton biomass, fish species, and fish biomass ($P < 0.05$), which may be related to the metabolic activities of aquatic organisms being temperature-dependent. pH has significant positive correlations with plankton biomass, benthic animal species, and benthic animal biomass ($P < 0.05$), suggesting that pH affects the survival and reproduction of these organisms within the studied range. COD and NH_3-N show consistent negative correlations with most aquatic community indicators, with NH_3-N having stronger negative effects (e.g., correlation with plankton biomass is -0.48, $P < 0.01$), highlighting their role as key pollutants. TP and TN exhibit positive correlations with aquatic community indicators, indicating that they act as nutrients supporting biological growth at current concentrations.

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Results of the construction of the water quality-aquatic biological community coupling relationship model

The multivariate linear regression model was constructed with the screened significant water quality indicators (DO, COD, NH_3-N, PH, and TN) as independent variables and the number of plankton species as the dependent variable. Let y represent the number of plankton species, x_1 represent the DO (mg/L), x_2 represent the COD (mg/L), x_3 represent theNH_3-N (mg/L), x_4 represent the TP (mg/L), x_5 represent the TN (mg/L), β_0 is the intercept, $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$ are the regression coefficients of each variable, and ε is the random error term. The formula of the multivariate linear regression model is:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \varepsilon \quad \text{(Eq.1)}$$

The estimated values of regression coefficients are: $\beta_0 = 12.3$, $\beta_1 = 0.8$, $\beta_2 = -0.5$, $\beta_3 = -1.2$, $\beta_4 = 0.3$, $\beta_5 = 0.4$, which can be obtained by substituting them into the above formula:

$$y = 12.3 + 0.8x_1 - 0.5x_2 - 1.2x_3 + 0.3x_4 + 0.4x_5 \quad \text{(Eq.2)}$$

The adjusted R^2 value of the model is 0.68, and the F test value is $25.6 (P < 0.01)$, indicating that the model fits the data well and can explain 68% of the changes in the number of plankton species. Similarly, a multivariate linear regression model of plankton biomass, benthic animal species, benthic animal biomass, fish species, fish biomass, and water quality indicators was constructed. The goodness of fit and significance test results of each model are shown in *Table 3*.

Table 3. *Results of the construction of the water quality-aquatic community coupling relationship model*

Dependent variables	Adjusting R^2	F	P
Plankton biomass	0.72	30.2	<0.01
Number of benthic animal species	0.65	22.8	<0.01
Benthic animal biomass	0.68	26.5	<0.01
Number of fish species	0.70	28.7	<0.01
Fish biomass	0.71	29.4	<0.01

By using the linear correlation between water environmental factors and characteristic parameters of aquatic biological communities, the influence of changes in different water quality indicators on the structure of marine biological communities is quantitatively evaluated, providing a powerful tool for predicting the impact of water quality changes on the structure of aquatic biological communities.

Results of the ecological threshold method

NH_3-N concentration is used as a water quality indicator, and the number of plankton species is used as an index of water body biological communities. The quantile regression results show that at the 0.25 quantile level, the number of plankton species will decrease

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by 1.5 for every increase of 1 mg/L in NH_3-N concentration; at the 0.75 quantile level, the number of plankton will decrease by 2.3 for every rise of 1 mg/L in NH_3-N concentration. This shows that the higher the NH_3-N concentration, the fewer plankton are present; after breakpoint regression analysis, 0.8 mg/L is determined as the ecological threshold. When the NH_3-N concentration is less than 0.8 mg/L, the relationship between the number of plankton and NH_3-N is -0.8; when the NH_3-N concentration exceeds 0.8 mg/L, its slope is -2.1. Combined with the Bootstrap resampling method for testing, this threshold has a high reliability ($P < 0.01$). Similarly, the results of ecological threshold analysis of other water quality indicators and the aquatic community index are shown in *Table 4*.

Table 4. *Results of ecological threshold analysis*

Water quality indicators	Aquatic community indicators	Ecological threshold	Change trend before and after the threshold
NH_3-N (mg/L)	Number of benthic animal species	0.7 mg/L	When it is below the threshold, the number of species decreases slowly; when it is above the threshold, the decline speed increases
COD (mg/L)	Fish biomass	20 mg/L	When it is below the threshold, the biomass increases; when it is above the threshold, the biomass begins to decrease
TP (mg/L)	Plankton biomass	0.15 mg/L	When it is below the threshold, the biomass increases; when it is above the threshold, the growth trend slows down

These thresholds are consistent with findings in related studies (e.g., Yin et al., 2024, reported a similar NH_3-N threshold for benthic communities in central Yunnan lakes), supporting their validity.

Discussion

Mechanism of the coupling relationship between water quality and aquatic biological communities

The intrinsic relationship between water quality indicators and the characteristics of aquatic biological communities was revealed by combining correlation analysis and regression model construction. The results show that the increased DO positively correlates with the number of aquatic organisms but negatively correlates with biomass. This aligns with the findings of Zhi et al. (2023), who emphasized DO's role in regulating aquatic community structure. Abundant DO is a favorable condition for the survival of aerobic organisms, which is conducive to species reproduction and the improvement of species diversity; however, excessive DO will intensify resource competition among organisms, inhibit the growth of certain microorganisms, and thus affect biomass accumulation.

The results show that the toxic effect of NH_3-N on aquatic organisms is the main reason for the decline in community indicators with increasing NH_3-N concentration. This is consistent with Yazman et al. (2024), who documented NH_3-N's inhibitory effects on aquatic organisms. High NH_3-N concentration will affect the osmotic pressure regulation, respiration, and enzyme activity in the water environment, destroy cell structure and function, hinder the growth of organisms, reduce reproductive capacity, and even cause

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death. The decomposition of organic matter in water bodies consumes a large amount of DO, forming an anoxic environment, and may also cause eutrophication of water bodies and changes in the structure of biological communities.

There is a significant positive correlation between TP and TN in water bodies and the biological communities in water bodies. This indicates that a specific concentration of nutrients can promote the growth of primary producers such as phytoplankton and affect the entire aquatic community through the food chain. However, when the concentration of nutrients exceeds a particular critical value, it will cause many algae to reproduce and bloom, thereby causing drastic fluctuations in DO in water bodies and deterioration of water quality, affecting the community structure of aquatic organisms. This finding is supported by Mânica and de Lima Isaac (2023), who observed similar nutrient-driven community shifts in eutrophied rivers.

Ecological significance of ecological thresholds and their application value

Ecological thresholds are the basis for evaluating and managing watershed ecosystem health. This project determined the NH_3-N ecological threshold (0.8 mg/L) for plankton species, which is slightly higher than the 0.7 mg/L threshold reported by Yin et al. (2024) for lake ecosystems, possibly due to river systems' higher resilience. This provides clear quantitative standards for the prevention and control of NH_3-N pollution in watersheds. When the NH_3-N concentration reaches or exceeds this critical value, managers can take targeted regulatory measures promptly, such as strengthening the monitoring of NH_3-N emissions from industrial wastewater, optimizing fertilization programs to reduce NH_3-N losses, and avoiding the deterioration of the biological community structure in the water body.

Determining the ecological threshold will provide a scientific basis for precisely implementing environmental restoration projects. For example, when the COD value exceeds 20 mg/L, the fish biomass begins to decline, suggesting that the COD value needs to be controlled below the threshold during the restoration process. This is consistent with Ramovha et al. (2024), who highlighted the importance of COD regulation in aquatic restoration. Establish a basin ecological compensation mechanism, clarify pollution responsibilities and protection results to improve the scientificity and effectiveness of basin environmental management.

Advantages of the applied approach

Compared with existing studies that focus on single water body types or small scales (Castro and Obusan, 2023), this study's multivariate linear regression model, validated across diverse aquatic ecosystems, better reflects the basin-scale coupling relationship. The integration of quantile regression and breakpoint regression for threshold analysis, combined with Bootstrap validation, improves the reliability of threshold determination, outperforming single-method approaches in previous research (Liu et al., 2022).

Uncertainty analysis

Although some results have been achieved, there are still many uncertain factors. In terms of data collection, although 120 sampling points were set up, due to the vast area and complex ecological environment of the Yangtze River Basin, the sampling points cannot cover all environmental types, and there is a problem of insufficient spatial representativeness. At the same time, although the sampling frequency during key periods

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has increased, it is still difficult to accurately reflect the instantaneous changes in water quality and aquatic communities, and the data integrity needs to be improved.

In terms of analytical methods, the multivariate linear regression model assumes that there is a linear relationship between the variables. In contrast, in actual ecosystems, the relationship between the water environment and the aquatic biological community may be more complex, with nonlinear relationships or time lag effects, which cannot entirely reflect the actual situation. In ecological threshold analysis, quantile and breakpoint regression methods greatly depend on the data's distribution characteristics.

In addition, due to the influence of human activities (such as water conservancy project construction, waterway dredging, etc.) and climate change (such as changes in precipitation patterns, extreme climate events, etc.), these factors may interact with water quality changes, thereby affecting the structure of aquatic biological communities and increasing the uncertainty of research results. Future research can further expand the sample size, optimize the sampling design, integrate nonlinear models with multi-source data, comprehensively consider the influence of multiple factors, and improve the reliability and universality of research results.

Conclusion

This study systematically analyzed the coupling relationship between water quality and aquatic biological communities in the Yangtze River Basin, China, and determined the ecological thresholds. The descriptive statistical results show that NH_3-N concentration has noticeable spatial differences (CV = 0.42) and temporal variability (peaking in rainy seasons). Correlation analysis revealed a complex correlation between water quality indicators and aquatic communities, such as a significant negative correlation between COD and fish biomass (correlation coefficient was -0.38, $P < 0.05$). The multiple linear regression model, validated across different water body types, quantified the impact of water quality changes with adjusted R^2 between 0.65 and 0.72. The results of the ecological threshold analysis showed key thresholds such as 0.8 mg/L for NH_3-N (plankton species) and 20 mg/L for COD (fish biomass). The results can clarify the evolution laws and key nodes of the basin ecosystem, and provide a scientific basis for the precise formulation of basin pollution prevention and control strategies, the implementation of ecological restoration projects, and the formulation of basin environmental management policies.

Conflict of interests. The authors declare no conflict of interests related to this article.

Data availability statement. The data that support the findings of this study are available upon reasonable request from the authors.

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