SEASONAL DYNAMICS AND WATER QUALITY ASSESSMENT IN SHILAN RESERVOIR, CHINA

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Abstract. Eutrophication, caused by excessive nutrient enrichment, is a major challenge to global aquatic ecosystems, particularly in regions with high anthropogenic pressures. Reservoirs, as critical water resources, are significantly impacted by nutrient dynamics influenced by climatic and hydrological factors. This study examines the seasonal dynamics of water quality in Shilan Reservoir, Linyi City, Shandong Province, China, emphasizing the impact of nutrient fluctuations on eutrophication and management strategies. Sampling at nine sites across four seasons revealed distinct seasonal trends in water quality indicators, including total nitrogen (TN) and total phosphorus (TP). TN levels in the summer ranged from inferior Class V (summer) to 6.20 mg/L (winter), while TP varied from 0.28 mg/L (spring) to 0.35 mg/L (winter), both exceeding permissible limits. Other parameters, such as pH, chemical oxygen demand, and biochemical oxygen demand, exhibited seasonal variations influenced by temperature and biological activity. Despite detectable levels of nitrate, iron, and manganese, these remained within acceptable standards, as did trace contaminants like heavy metals. The findings highlight a high nutrient load contributing to eutrophication, particularly in summer and autumn. The study underscores the need for targeted nutrient management strategies to control TN and TP, coupled with advanced monitoring technologies such as remote sensing for real-time assessments. These efforts aim to improve reservoir health and mitigate ecological risks, providing insights into sustainable water resource management under changing climatic conditions.

Keywords: *anthropogenic impact, climate variability, water pollution, reservoir management, environmental monitoring*

Introduction

Eutrophication, characterized by the excessive enrichment of water bodies with nutrients like nitrogen and phosphorus, has been a persistent global environmental issue (Schaffner et al., 2010; Sinha et al., 2017; Kakade et al., 2021; Akinnawo, 2023; Soana et al., 2024; Yang et al., 2025). It disrupts aquatic ecosystems by promoting the overgrowth of algae and other plants, leading to oxygen depletion and loss of biodiversity (Naeem et al., 2014; Li and Gao, 2018; Gao and Zhao, 2020). The phenomenon is predominantly controlled by nutrient inputs, particularly from agricultural runoff, sewage, and industrial effluents, and is influenced by factors such as hydrology and food webs (Yang et al., 2022; Zhang et al., 2024).

In recent years, there have been significant advances in understanding the dynamics of nutrient cycling in freshwater ecosystems, particularly with the integration of climate variability into models of nutrient dynamics (Brookfield et al., 2023). Studies have shown that seasonal temperature changes can significantly influence nutrient cycling processes, such as nitrification and denitrification, which are critical in controlling nitrogen levels in water bodies (Chambers et al., 1999). Furthermore, phosphorus cycling has been found to be less sensitive to temperature variations, although it is affected by seasonal phytoplankton uptake, particularly during warmer months (Duhamel, 2025). These findings underscore the complex interplay between temperature, biological activity, and nutrient fluxes in aquatic environments. Consequently, accurately modeling nutrient cycling in freshwater ecosystems requires not only an understanding of ecological processes but also the incorporation of climate variability as a key factor influencing nutrient dynamics.

Recent research suggests that climate variability, such as temperature fluctuations and seasonal precipitation patterns, plays a vital role in modulating nutrient concentrations and their ecological impacts (Summers and Ryder, 2023). This is particularly relevant for reservoirs, where long retention times can exacerbate nutrient accumulation. Consequently, incorporating seasonal dynamics into eutrophication models has become a critical focus of recent studies, with efforts aimed at predicting nutrient fluxes under various climatic scenarios. Such approaches provide a more accurate assessment of nutrient loads and the risks of harmful algal blooms (Glibert, 2017; Ho et al., 2019).

In China, maintaining a healthy and stable aquatic environment is a critical component of the national goal for developing an ecocivilization, which includes the harmonious coexistence of “mountains, waters, forests, farmlands, lakes, and grasslands” (Liu et al., 2023). Reservoirs play a vital role in China’s water management strategy, serving as crucial water storage and supply systems. Ensuring the health of reservoir water environments is, therefore, of paramount importance for water security, which is essential for the country’s sustainable development and the well-being of its population. At the 75th session of the UN General Assembly, General Secretary Xi Jinping proposed that China aims to achieve carbon peak by 2030 and carbon neutrality by 2060 (Fuhrman et al., 2021). This ambitious goal reflects China’s commitment to addressing climate change and promoting environmental sustainability. Achieving these targets will require a comprehensive approach, including measures to mitigate eutrophication and improve water quality. Efforts to reduce nutrient inputs, promote sustainable agricultural practices, enhance wastewater treatment, and restore natural ecosystems will be critical in tackling eutrophication and ensuring the long-term health of China’s water bodies (Novotny, 2011). By addressing eutrophication, China can not only protect its aquatic environments but also contribute to global efforts to safeguard water resources and promote a sustainable future for all (Ning et al., 2024).

In recent years, the dynamics of nutrient cycling in reservoir waters have become an important area of research in aquatic environmental studies. The cycling of nutrients in water not only affects water quality but is also closely related to eutrophication, ecological health, and the sustainable management of water resources. Although numerous studies have explored nutrient cycling in various types of water bodies, research on specific regions and reservoirs remains insufficient. To further enhance our understanding of nutrient dynamics in reservoirs, this study selects Shilan Reservoir as the research object.

Shilan Reservoir, located in Linyi, China, is a medium-sized freshwater reservoir with distinct hydrological characteristics that set it apart from other water bodies. The reservoir is fed primarily by precipitation and seasonal inflows from the Xuezhuang River, a tributary of the Beng River. Due to its moderate depth (ranging from 10 to 35 m) and relatively long hydraulic retention time of approximately 60 days, the reservoir exhibits strong seasonal stratification, which affects nutrient cycling and oxygen availability. Another distinguishing feature of Shilan Reservoir is its semi-closed hydrological nature, meaning that water exchange is relatively limited, leading to higher susceptibility to nutrient accumulation and eutrophication, particularly in summer and autumn. The reservoir is surrounded by agricultural and urbanized areas, contributing to significant external nutrient loading through runoff and wastewater discharge. Additionally, the regional monsoon climate plays a crucial role in shaping the hydrological dynamics, with heavy rainfall in summer leading to increased inflow and sediment resuspension, whereas drier winter months result in reduced water levels and higher concentrations of pollutants due to limited dilution. These unique hydrological and environmental conditions make Shilan Reservoir an ideal study site for understanding seasonal nutrient variations and the impacts of external loading on water quality. It has long served as one of the main water sources for the local area, holding significant economic and ecological value. Furthermore, the reservoir’s water experiences seasonal variations and is influenced by surrounding land use and climate change, resulting in a representative nutrient cycling pattern. Therefore, Shilan Reservoir, as a research object, not only reflects the nutrient dynamics of typical reservoirs but also provides valuable insights for the management and protection of other similar reservoirs.

While many studies have explored nutrient cycling in freshwater systems, research on midsized reservoirs like Shilan Reservoir remains limited. Regional factors such as lo-cal hydrology, land use, and climate create unique nutrient dynamics that general studies often overlook. Existing research also lacks detailed insights into how seasonal climatic changes affect nitrogen (TN) and phosphorus (TP) cycling in such reservoirs. This study addresses these gaps by analyzing seasonal variations of TN and TP in Shilan Reservoir, highlighting the impacts of local climate and human activities on nutrient dynamics. The findings provide region-specific insights and practical guidance for improving reservoir management, offering valuable references for similar water bodies facing environmental and climatic challenges.

Materials and methods

Site description and sampling procedure

Shilan Reservoir is a medium-sized reservoir located in the upper reaches of the Xuezhuang River, a tributary of the Beng River, within the Yi River watershed. Constructed in 1960, it serves as a crucial drinking water source for rural communities and controls a drainage area of 79 km² with a total capacity of 400 million m³. The reservoir’s geographic characteristics and its role in local water management make it a key focus of water quality monitoring.

Water samples were collected from nine sites throughout four seasons: summer (July), fall (October) 2022, and winter (January) and spring (April) 2023. These sites were selected to capture spatial variability within the reservoir, although further analysis using spatial interpolation techniques like kriging could enhance the understanding of spatial variations in water quality. Nine sites across the reservoir were chosen to represent different areas (e.g., inflow, outflow, and middle sections). Water samples were collected from the surface layer (0-0.5 m) using 2.5-L clean plastic containers. Samples were transported to the laboratory on ice, ensuring their integrity until analysis. In the laboratory, key water quality parameters such as nutrient concentrations, pH, ammonia nitrogen, permanganate index (PI), 5-day biochemical oxygen demand (BOD_5), total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD) were measured (*Fig. 1*).

Water temperature and transparency were not directly measured in this study due to logistical constraints and a focus on nutrient dynamics. However, temperature influences were inferred through seasonal variations in nutrient levels, and transparency was indirectly reflected in turbidity and organic matter measurements. Future studies should incorporate these parameters to provide a more comprehensive assessment of water quality dynamics.

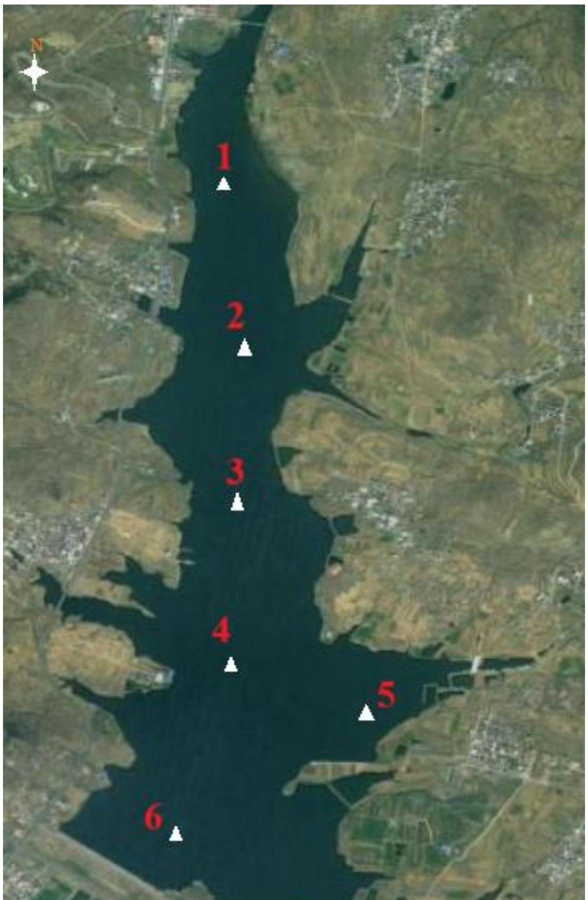

Figure 1. *Water quality sampling map of Shilan Reservoir, China*

Analytical methods

Spectrophotometric measurements were carried out using a UV-1750 ultraviolet-visible spectrophotometer (A11605031003CS). Method validation included interlaboratory calibration to ensure the reliability of spectrophotometric readings, and recovery studies were performed for key indicators such as TN and TP, with recovery rates exceeding 95% for all measured parameters. Results indicated that TN and TP levels were consistently above the permissible limits in all seasons, contributing to the eutrophic state of the reservoir.

For spectrophotometric measurements, recovery studies were conducted to evaluate method performance. The recovery rates for TN, TP, and ammonia nitrogen consistently exceeded 95%, ensuring high accuracy. Calibration curves for each parameter were generated with standards prepared in triplicate. Interlaboratory calibration was conducted by comparing results from independent laboratories using certified reference materials. The calibration results showed a strong correlation ($R^2 > 0.99$), confirming the robustness of the analytical methods.

Water quality evaluation

The water quality of Shilan Reservoir was assessed based on China’s Surface Water Environmental Quality Standards (GB 3838-2002). Classification of PI, BOD_5, COD, TN, TP, and ammonia nitrogen was performed according to the standards, with classes ranging from I (highest water quality) to V (lowest water quality).

Statistical and spatial analysis

Data were analyzed for seasonal trends and correlations between the water quality parameters. However, a detailed spatial variation analysis was not explicitly performed due to the limited number of sampling sites (nine locations) and the primary focus of this study on seasonal nutrient dynamics. While the selected sites captured spatial variability within the reservoir, a high-resolution spatial assessment would require more extensive sampling points and interpolation methods such as kriging. Future studies should incorporate geostatistical approaches and remote sensing techniques to enhance spatial resolution and provide a more comprehensive understanding of water quality distribution patterns. PCA is performed by standardizing the data, computing the covariance matrix, extracting its eigenvalues and eigenvectors, selecting the top eigenvectors based on their eigenvalues, and projecting the data onto these principal components to reduce dimensionality while retaining maximum variance.

Results

Seasonal dynamics of water quality indicators

The seasonal dynamics of water quality indicators in Shilan Reservoir are depicted in *Figure 2*. The pH values varied across seasons, with significantly higher values in fall compared to spring and winter ($p < 0.01$). For PI, the values in summer were significantly higher than in spring ($p < 0.01$). For COD, the seasonal trend was fall > spring > winter > summer, with significantly higher levels in fall compared to other seasons ($p < 0.05$). For BOD_5, the seasonal trend was summer > winter > fall > spring, with highly significantly higher values in summer and winter compared to fall and spring ($p < 0.01$). Ammonia nitrogen concentrations were significantly higher in spring and summer compared to fall and winter ($p < 0.05$). TP exhibited significant seasonal differences ($p < 0.01$), with higher values in spring compared to other seasons.

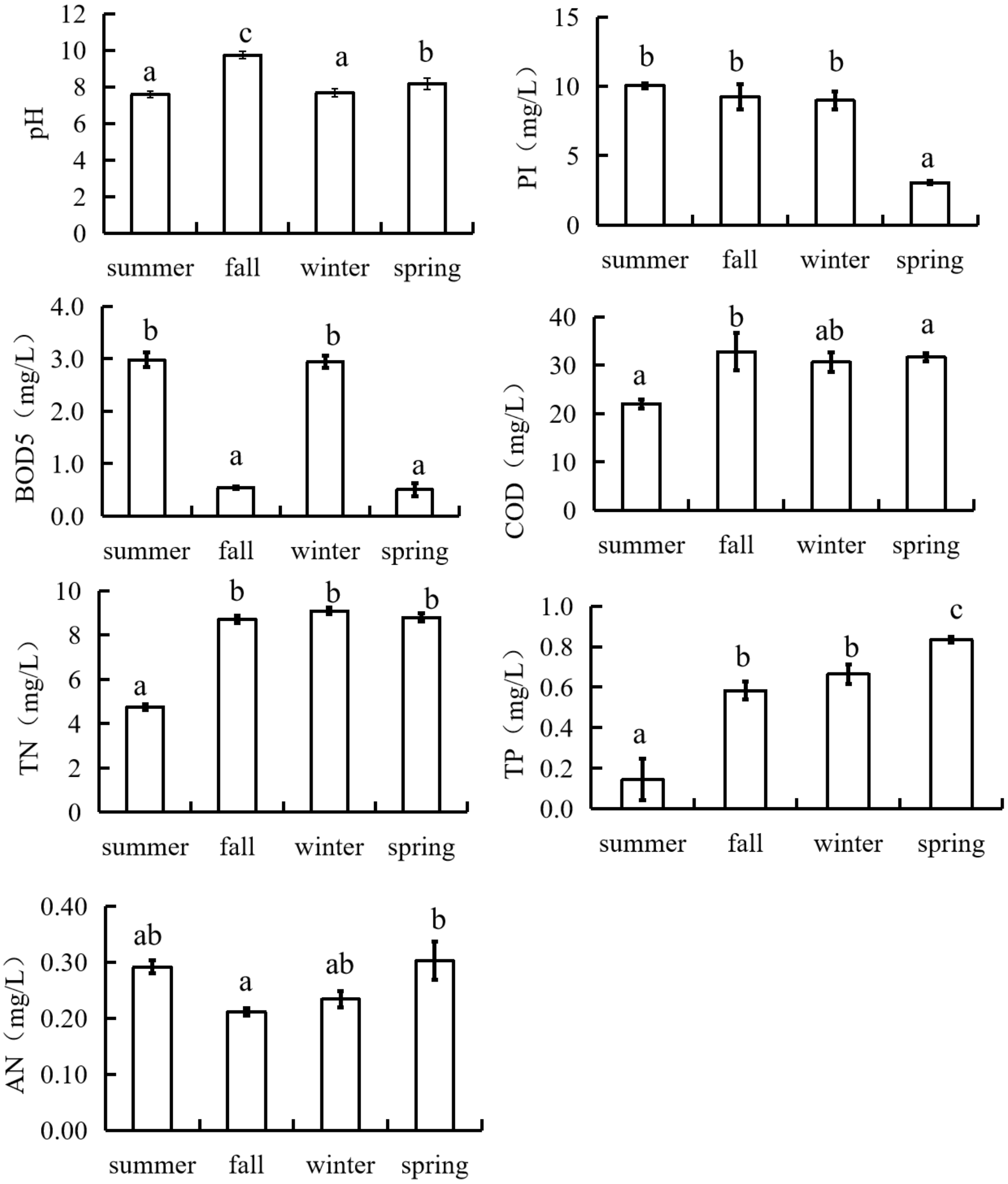

***Figure 2.** Seasonal mean of water quality indicators in Shilan Reservoir, China. pH, permanganate index (PI), 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), and ammonia nitrogen, AN, ammonia nitrogen*

Water quality evaluation

The water quality of Shilan Reservoir was evaluated based on the Surface Water Environmental Quality Standards (GB 3838-2002), which classify water quality into five classes: Class I (highest quality, suitable for drinking water sources with minimal treatment), Class II (good quality, suitable for centralized drinking water supply), Class III (moderate quality, suitable for fisheries and swimming), Class IV (polluted, suitable for industrial and agricultural water supply), and Class V (poor quality, unsuitable for direct human contact or ecological functions). The classification of permanganate index (PI), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), and ammonia nitrogen (AN) was performed according to these national standards. The ranges for each class are presented in *Table 1*. Water quality classification was determined using the "worst parameter" approach, meaning that the overall classification of a water sample was assigned based on the parameter with the poorest quality rating among the six indicators. This method ensures a conservative assessment of water quality conditions and highlights the limiting factors affecting water usability.

The results showed the following classes for several water quality indicators as follows: PI, the water quality was Class V in summer, IV in fall and winter, and II in spring; BOD_5, Class IV in summer and V in other seasons; COD, Class II in summer and winter, and I in fall and spring; TN, inferior Class V in all seasons; TP, Class V in summer and inferior Class V in other seasons; ammonia nitrogen, Class II in all seasons.

The pH, nitrate, iron, and manganese levels in Shilan Reservoir were all within permissible limits. The concentrations of volatile phenols, cyanides, chromium, arsenic, mercury, selenium, lead, copper, zinc, and cadmium were not detected in the water samples, and their levels, if present, are expected to be very low and within the standards for Class I water.

Table 1. *Classification of the water quality of Shilan Reservoir, China*

Parameter	Class I (Best)	Class II	Class III	Class IV	Class V (Worst)	Shilan Reservoir (seasonal classification)
PI (mg/L)	≤2.0	2.0 - 4.0	4.0 - 6.0	6.0 - 10.0	>10.0	Summer: V, Autumn: IV, Winter: IV, Spring: II
BOD_5 (mg/L)	≤3.0	3.0 - 4.0	4.0 - 6.0	6.0 - 10.0	>10.0	Summer: IV, Autumn: V, Winter: V, Spring: V
COD (mg/L)	≤15	15 - 20	20 - 30	30 - 40	>40	Summer: II, Autumn: I, Winter: II, Spring: I
TN (mg/L)	≤0.2	0.2 - 0.5	0.5 - 1.0	1.0 - 1.5	>1.5	All seasons: Inferior Class V
TP (mg/L)	≤0.02	0.02 - 0.1	0.1 - 0.2	0.2 - 0.3	>0.3	Summer: V, Autumn: Inferior V, Winter: Inferior V, Spring: Inferior V
AN (mg/L)	≤0.15	0.15 - 0.5	0.5 - 1.0	1.0 - 1.5	>1.5	All seasons: II

PI, permanganate index; BOD_5, 5-day biochemical oxygen demand; COD, chemical oxygen demand; TN, total nitrogen; TP, total phosphorus; AN, ammonia nitrogen

Correlations among water quality indicators

Correlations among water quality indicators in Shilan Reservoir were evaluated (*Table 2*). The pH showed a significant negative correlation with BOD_5 and ammonia nitrogen, and a significant positive correlation with TN. The PI was highly significantly positively correlated with BOD_5, and significantly negatively correlated with TP and ammonia nitrogen. The BOD_5 was significantly negatively correlated with TN and TP. The COD was highly significantly positively correlated with TN and TP. Lastly, TN and TP were highly significantly positively correlated with each other. Correlations among other factors were not significant.

Table 2. *Correlations among water quality indicators of Shilan Reservoir, China*

	pH	**PI**	**BOD_5**	**COD**	**TN**	**TP**	**AN**
pH	1.000						
PI	0.104	1.000					
BOD_5	−0.723**	0.503**	1.000				
COD	0.277	−0.266	−0.295	1.000			
TN	0.307*	−0.281	−0.391*	0.448**	1.000		
TP	0.133	−0.562**	−0.502**	0.503**	0.824**	1.000	
AN	−0.334*	−0.346*	−0.059	−0.096	−0.262	0.061	1.000

PI, permanganate index; BOD_5, 5-day biochemical oxygen demand; COD, chemical oxygen demand; TN, total nitrogen; TP, total phosphorus; AN, ammonia nitrogen
*, $p < 0.05$; **, $p < 0.01$

The important factors influencing water quality

The PCA results show that the first two principal components (PC1 and PC2) explain about 79.6% and 15.1% of the variance, respectively, totaling 94.7% (*Fig. 3*). The primary influencing factors based on component loadings for PC1 and PC2 are as follows: PC1 is dominated by COD (chemical oxygen demand) with a strong positive loading, indicating that organic pollution significantly influences water quality variation. PC2 is primarily influenced by PI, suggesting the impact of oxidation-related processes.

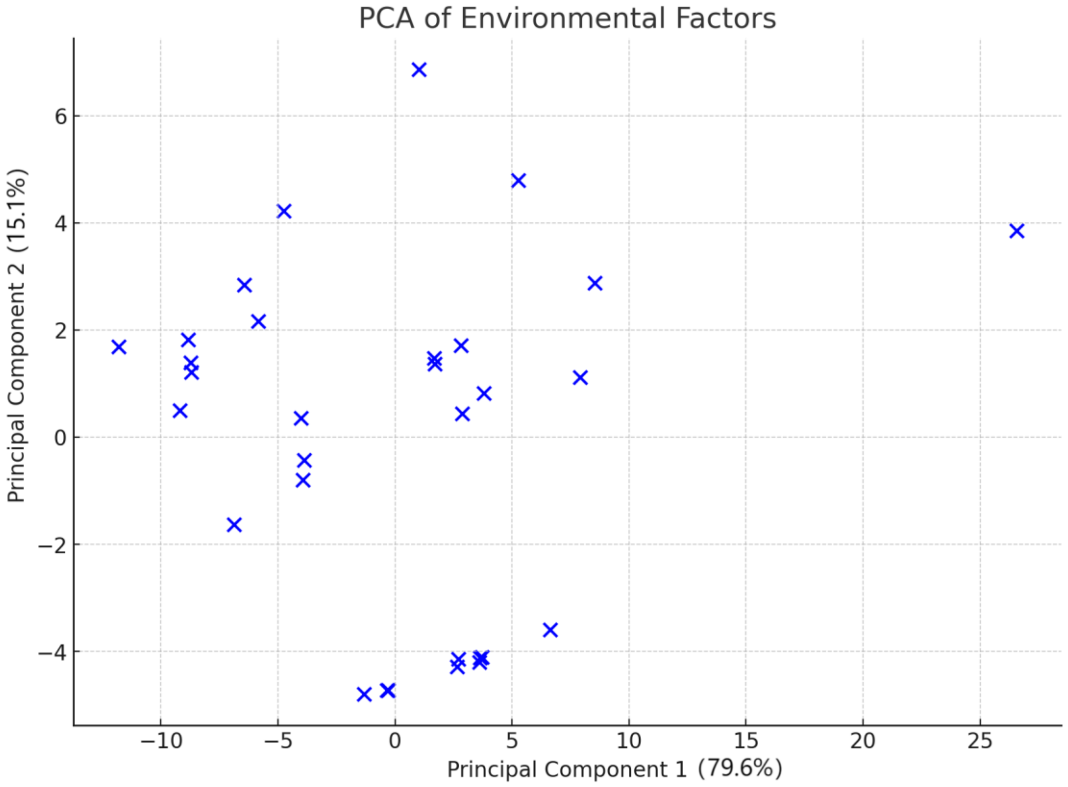

Figure 3. *The results of the principal component analysis*

However, water quality is not only determined by these internal physicochemical parameters but also affected by external anthropogenic and environmental factors. Potential anthropogenic drivers include agricultural runoff, industrial discharge, and domestic wastewater, which contribute to nutrient and organic matter loading. Additionally, environmental factors such as seasonal precipitation, land use changes, and hydrodynamic conditions may influence pollutant transport and accumulation in the reservoir. Although water temperature and transparency were not directly measured in this study, their influence on nutrient cycling and phytoplankton growth is well-documented. Temperature fluctuations affect microbial activity and biochemical processes such as nitrification and denitrification, while transparency regulates light availability for primary production. Future studies should incorporate these parameters to better understand their roles in seasonal water quality changes. Additionally, a more detailed spatial analysis is needed to capture fine-scale variations in water quality across the reservoir. Given the limited number of sampling sites in this study, we were unable to conduct an in-depth spatial interpolation of water quality parameters. Advanced spatial modeling techniques, such as kriging, and remote sensing methods can be integrated in future research to provide high-resolution spatial mapping of water quality dynamics. Such approaches will enable more precise identification of pollution hotspots and contribute to improved reservoir management strategies.

Discussion

Water quality indicators was the main participants in the reservoir ecosystem, and nutrients were the key factors leading to water eutrophication (Zheng et al., 2015; Zeng et al., 2025; Wang et al., 2025). Nitrogen (N) and phosphorus (P) are the key driving forces of algae growth, and also one of the important factors causing water eutrophication (Liu et al., 2022). In our study, the TN decreased in the order of winter > spring > fall > summer, with highly significantly lower values in summer compared to other seasons, which is consistent with the previous study (Soana et al., 2024). However, unlike some studies where nutrient concentrations did not show clear seasonal patterns (Gopal and Sharma, 1984), our findings highlight a distinct seasonal trend, suggesting regional climatic and hydrological factors may play a significant role in the seasonal distribution of nitrogen in the water body. Previous studies have shown that N relies on key microbial processes such as nitrification and denitrification, which is highly temperature-dependent and sensitive to warming, so N content in water is affected by temperature rise (Velthuis and Veraart, 2022; Soana et al., 2024). This is in agreement with studies that emphasize the microbial-driven nitrogen cycle is heavily influenced by rising temperatures, which accelerates both nitrification and denitrification rates, although the extent of these processes can vary significantly depending on local microbial communities and water chemistry (Albert et al., 2008).

However, the TP levels showed a seasonal variation, with the highest values observed in spring and winter. This trend may be attributed to multiple factors. First, phosphorus inputs from external sources, such as agricultural runoff and wastewater discharge, tend to be more pronounced during wetter seasons, particularly in spring, due to increased precipitation and surface runoff. Second, internal phosphorus cycling within the reservoir may contribute to the observed pattern. During winter, reduced biological activity and lower temperatures can lead to phosphorus accumulation in the water column due to decreased uptake by phytoplankton. In contrast, in warmer seasons, phytoplankton growth can enhance phosphorus assimilation, temporarily reducing TP concentrations in the water (Soana et al., 2024). Additionally, sediment resuspension caused by hydrodynamic disturbances, such as strong winds and increased inflow in certain seasons, may lead to the release of phosphorus from bottom sediments into the water column, further influencing TP levels (Poulton et al., 2019; Li et al., 2024). These combined factors highlight the complexity of phosphorus dynamics in the reservoir and suggest that both external loading and internal biogeochemical processes play crucial roles in TP fluctuations (Ylla et al., 2007; Solovchenko et al., 2019; Burrows et al., 2021). Future studies should focus on quantifying the relative contributions of these factors to better inform nutrient management strategies.

With ongoing climate change, rising temperatures may further influence the dynamics of both TN and TP. This is achieved by intensifying temperature-sensitive microbial and phytoplankton processes. For nitrogen, warmer temperatures could amplify microbial nitrification and denitrification rates, causing a seasonal shift in TN availability and potentially exacerbating eutrophication during warmer months. Phosphorus uptake could also be further enhanced, as increased temperatures favor phytoplankton growth, leading to higher P removal rates from the water but also increasing the risk of nutrient limitation for other species. Such temperature-driven effects underscore the importance of considering climate change in nutrient management practices for reservoirs, as temperature shifts may lead to greater fluctuations in nutrient levels and a heightened risk of eutrophication.

In addition, by determining the PI, we can understand that the content of organic matter in the water is highest in the summer (Xie and Gong, 2024), which means that the pollution degree of the water is highest in the summer. Besides, previous study indicated that organic matter bioavailability was significantly higher during summer compared to other seasons (Song et al., 2015). Therefore, with the increase of water temperature, nutrients are continuously enriched, and the growth rate of microorganisms, algae and other organisms in the water body is accelerated (Zhao et al., 2024). However, when the temperature is too high, the growth rate of algae decreases dramatically (Ras et al., 2013), which also explains that the bloom phenomenon in the northern reservoirs of China mainly occurs in autumn rather than summer, the water bloom in Hoover Reservoir in the United States is prone to occur during the summer and autumn seasons (Allen et al., 2020). This observation is in line with other studies on northern Chinese reservoirs, where researchers noted a seasonal shift in bloom dynamics, often driven by the interplay between nutrient availability and temperature thresholds for algal growth (Fu et al., 2012).

Through seasonal investigations and studies, we found that temperature caused changes in nutrients in the water body, which in turn affected the eutrophication of the reservoir, which is consistent with previous studies (Savichtcheva et al., 2015; Zhao et al., 2022). However, in contrast to some regions where nutrient cycling and eutrophication are predominantly influenced by anthropogenic inputs year-round (Ge et al., 2020), our study suggests a stronger temperature-mediated effect, particularly in late summer and autumn. The reservoir in north China containing Shilan Reservoir is affected more and more seriously by industrial sewage, agricultural drainage and domestic sewage (Xie et al., 2020), and the main pollution indicators are TN and TP (Powers et al., 2015; Yang et al., 2020). Similar results are obtained in this study: TN, inferior Class V in all seasons; TP, Class V in summer and inferior Class V in other seasons. These findings are in agreement with previous assessments that have highlighted the persistent nutrient pollution in northern Chinese reservoirs, although some studies report slightly better water quality in other regions, likely due to differences in industrial and agricultural pollution sources (Hallberg, 1987). PI, Class V in summer, IV in fall and winter, and II in spring; BOD_5, Class IV in summer and V in other seasons; According to the results of water quality evaluation, the pollution degree of the Shilan Reservoir is the highest in summer and autumn. In order to reduce the harm of Shilan Reservoir eutrophication, it is necessary to further study the relationship between N and P cycle in water and water temperature, so as to guide the decision-making of Shilan Reservoir protection and restoration. Moreover, comparisons with similar water bodies across northern China suggest that integrated nutrient management practices, such as controlling agricultural runoff and improving wastewater treatment, could significantly reduce TN and TP levels, especially in summer months (Novotny, 2011).

The soil carbon, nitrogen, and phosphorus nutrient content in Mengshan and Tashan within the Shilan Reservoir watershed is relatively high (Gao and Wang, 2018; Wang et al., 2021), which raises the baseline values of water bodies dominated by nitrogen and phosphorus nutrients. Both belonging to the Yi River Basin, Shilan Reservoir and nearby Yi River (Li and Gao, 2018; Xu et al., 2019), Yunmeng Lake (Dai et al., 2016), and Wuzhou Lake (Gao and Zhao, 2020) are highly affected by nitrogen and phosphorus nutrients.

Conclusion

This study analyzed the seasonal dynamics and water quality of Shilan Reservoir, revealing that TN and TP consistently exceeded permissible limits, contributing to eutrophication. Temperature was identified as a key driver of seasonal nutrient changes, while industrial discharge, agricultural runoff, and domestic sewage also significantly impacted water quality. To address these issues, targeted nutrient management strategies are needed, particularly during summer and autumn. Measures such as reducing nutrient inputs, improving wastewater treatment, and utilizing real-time monitoring technologies like remote sensing are essential for reservoir health. Future research should focus on high-resolution spatial analysis and long-term monitoring to better understand the factors influencing nutrient dynamics. These findings provide valuable insights for sustainable water resource management and effective eutrophication control in Shilan Reservoir and similar ecosystems.

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