WATER QUALITY TRENDS BASED ON MANN–KENDALL TEST AND RESCALED EXTREME DIFFERENCE ANALYSIS: A CASE STUDY OF SHANXI RESERVOIR, CHINA

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Abstract. Ensuring stable water quality standards in drinking water source reservoirs plays a decisive role in ensuring water safety. In this study, a series of indicators such as secchi disk transparency (SD), permanganate index (COD_{Mn}), total phosphorus (TP), total nitrogen (TN), ammonia nitrogen (NH_3-N) and *Chlorophyll*.a (*Chl*.a) were used to detect and characterize the water quality of Shanxi Reservoir in Wenzhou, China. And explore the water quality change points by combining the Water Pollution Index (WPI), Mann–Kendall test and rescaled extreme difference analysis. The results show that the overall water quality of Shanxi Reservoir is excellent and can safely perform its watershed function. The water quality pollution index value in the reservoir area showed an increasing trend, with an overall value range of 0.34-0.94. The water quality was monitored in the process of organic pollution, phosphorus and NH_3-N with a significant trend of improvement. Future trends in water quality indicate that water quality in the reservoir will not deteriorate. Change points for SD, *Chl*.a, TN and COD_{Mn} occur in May 2019, December 2019, December 2018 and May 2021, NH_3 -N and TP have no water quality change points throughout the monitoring process. It is recommended to avoid nitrogen pollution in water bodies to prevent harming water ecological safety.
Keywords: *Shanxi Reservoir, water quality, Mann–Kendall test; R/S analysis, change trend*

Introduction

The pressure of environmental change and increased pollution has made the deterioration of water quality in water bodies such as rivers, lakes and underground aquifers a serious concern worldwide. The increasingly visible problem of water pollution has led to serious ecological and environmental problems (Ma et al., 2009), with additional scientific and engineering aspects, as well as significant impacts at the social, legal, economic and political levels. Reduced reserve water capacity and exposure to pollution are affecting the sustainability of water resources in both breadth and depth (Chen et al., 2016). Although many countries have implemented water quality protection measures and monitoring systems (Behmel et al., 2016), improving water supply and combating water pollution at the right point in time is still a challenge (Wu et al., 2017). Therefore, scientific assessment of water quality and understanding of its trends is an important issue for sustainable water use and environmental management.

Shanxi Reservoir is a large centralized drinking water reservoir with the largest number of beneficiaries, located at the middle section of the main stream of Feiyun River in Wenzhou. The lake is mainly used for water supply, power generation, irrigation and flood control. Unfortunately, due to the construction of the reservoir, the original hydrological and hydrodynamic conditions in the reservoir area were changed, and the water quality began to deteriorate after the reservoir was built, with an outbreak of “water wars” in 2010 (Yang et al., 2010). In 2010, the water quality began to

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deteriorate after the reservoir was built, and “water bloom” broke out. However, the reservoir, as the “big water tank” of Wenzhou citizens, needs to strengthen the protection of water quality in the reservoir area to ensure the water safety of residents.

The purpose of this study was to detect trends in water quality in this reservoir over the past 5 years (2017-2021) by conducting a comprehensive data analysis. Due to the limitation of data availability, only a limited number of water quality parameters were analyzed. To test a set of hypotheses regarding the statistical nature of the time series, a non-parametric test was used. Compared to parametric tests, it does not require variance chi-square or a priori assumptions on the distribution of the data samples and is less sensitive to outliers (Patakamuri et al., 2020). Since the Mann–Kendall test statistic is determined by the rank-sum series of the time series rather than the original values, it is credible when dealing with non-normally distributed data and time series with censored data (Quan et al., 2018). The Mann–Kendall test is commonly used in hydrology and water quality studies (Dong et al., 2016; Quan et al., 2018; Jung et al., 2019; Chen et al., 2019), and plays a key role in identifying trends in time series data. Trend analysis helps to statistically determine whether the value of a random variable is decreasing or increasing over time. The test has properties such as simplicity, reliability, and the ability to cope with missing data.

In this study, the aim was to provide a basis for decision-making on the ecological environment management of local drinking water sources. Shanxi reservoir was used as the study area for water quality evaluation by using the single factor evaluation method, exploring the temporal change characteristics of water environment indicators from 2017-2021 by Mann–Kendall test, and analyzing the future change characteristics by using the rescaled polar difference method. These findings can be used as a theoretical basis for the comprehensive treatment of water quality in Shanxi Reservoir, and can also look forward to the water environment safety of this reservoir.

Materials and methods

Overview of the study area

Shanxi Reservoir (27.46°~27.99°N, 119.62°~120.27°E), located in Wencheng County, Wenzhou City, Zhejiang Province, China (*Fig. 1*), is the largest drinking water reservoir in Zhejiang Province, with a normal storage level of 142 m. As a large reservoir, Shanxi Reservoir plays a vital role in drinking water supply, flood control, agriculture and aquaculture. And Shanxi Reservoir was put into operation in 2000. By the end of 2021, the total water storage in Shanxi Reservoir was 1.037 billion m^3, accounting for 79.59% of the total water storage in the city’s large and medium-sized reservoirs.

Water quality indicators and data

The monthly water quality of Shanxi Reservoir was evaluated according to the *Environmental Quality Standard for Surface Water* (GB3838-2002) for the period of 2017-2021. The origin data was from Water Environment Quality Monitoring Website of the People’s Republic of China. In this study, representative indicators were selected, with transparency (SD) as a physical indicator, permanganate index (COD_{Mn}), total phosphorus (TP), total nitrogen (TN) and ammonia nitrogen (NH_3 -N) as chemical indicators, and chlorophyll a (*Chl*.a) as a biological indicator.

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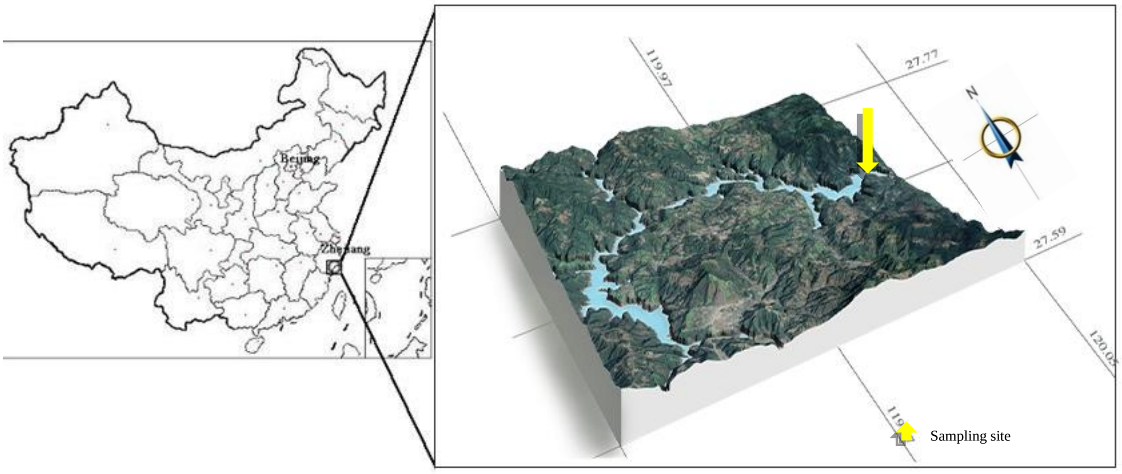

Figure 1. *Location of the study area*

In order to enhance the interpretation of the water quality status and quality level assessment results, the water pollution index (WPI) is used (Milijasevic et al., 2011) to assess the physical, chemical and ecological conditions and to reflect the effects of various stresses in Shanxi Reservoir. The *WPI* calculation is shown in *Equation 1*.

$$WPI = \frac{1}{n} \times \sum_{i=1}^{n} \frac{C_i}{S_i} \qquad \text{(Eq.1)}$$

In *Equation 1*, *WPI* indicates the integrated water pollution index. C_i denotes the concentration of the i^{th} water quality index measured (mg/L), the S_i denotes the standard concentration of the i^{th} water quality index (mg/L), n is the number of water quality indicators.

Water quality change trend test

Mann–Kendall test

In order to avoid water quality indicators by flow and precipitation, Mann–Kendall test is chosen to analyze the long-term trend of water quality series. Mann–Kendall test is a non-parametric method based on the rank. The Mann–Kendall test is a non-parametric method based on rank and has been widely used to detect trends in water quality time series (Hamed, 2009). In order to avoid the length of time on the water quality trend judgment, choosing 5-8 years of data is better. The calculation process is divided into three steps (Wu et al., 2020): (1) month by month calculation of the difference statistic and its corresponding variance; (2) these are summed to obtain the presidential measure and the total variance; (3) to obtain the test statistic (Z) and the significance level (α). When Z > 0, it indicates that the water quality index data in the time series has an upward trend; Z = 0, means no trend and Z < 0 shows a downward trend. When α = 0.05, Z = 1.96, it indicates that this has statistically significant.

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Rescaled extreme variance analysis (R/S analysis)

Hurst index obtained by using rescaled polar difference analysis can indicate the future trend of water quality change, through the fractal characteristics of the index, can determine the future trend of water quality change and the past is consistent. Its calculation process is divided into three steps (Wu et al., 2020): (1) the water quality indicators in accordance with the time series sorting; (2) then calculate the cumulative deviation, extreme deviation and standard deviation of the data; (3) calculate the Hurst index.

Results and discussion

Time variation characteristics of water quality indicators

Water temperature is one of the parameters that directly or indirectly affects other water quality determinants (such as pH, dissolved oxygen and alkalinity) (Mishra et al., 2009). Surface water temperatures in Shanxi Reservoir ranged from 11.7-33.0 °C throughout the study period. The highest surface water temperatures during the monitoring years were mostly recorded during July-September, while the lowest water temperatures were recorded in February during the winter months for all years. The higher pH values witnessed an increase in the productivity of the lake (Siriwardana et al., 2019). The water body of Shanxi Reservoir was overall weakly alkaline (6.68-8.90) during 2017-2021, with the maximum pH of the water body occurring in summer (July-September). Dissolved oxygen depends on many factors, such as temperature, photosynthetic activity, wind action, biological respiration, pollution load, etc. Its overall value range is 6.20-9.31 mg/L. The temporal variation characteristics of each water quality indicator in Shanxi reservoir are shown in *Figure 2*. The SD values of water bodies range from 1.00-4.37 m (*Fig. 2a*), with small values in the first three years and an increase in SD values since 2020, indicating that the reservoir water bodies are on the poor side of nutrients and have a small phytoplankton population. *Chl*.a has significant seasonal characteristics, and the water bodies have high outbreak eutrophication potential in summer and autumn (*Fig. 2b*).

Inorganic nitrogen is the most common form of nitrogen found in natural water. It is the main nutrient salt that accelerates the growth of aquatic plants and aquatic algae (Yan et al., 2020) and therefore the potential ecological risk of ammonia nitrogen is high. *Figure 2c* shows the concentration of ammonia nitrogen in the reservoir during the study, the concentration of NH_3 -N in the reservoir fluctuated between 0.020-0.28 mg/L with a mean value of 0.073 mg/L, where the peak occurred in January 2017. Higher NH_3 -N concentrations were observed during the summer period with a mean value of 0.079 mg/L, followed by 0.074 mg/L in the fall. Due to increased rainfall, nitrogenous pollutants from farming effluents around the reservoir influx into the reservoir through surface runoff (Zhao et al., 2021) The nitrogen and salt levels in the reservoir increased during summer (*Fig. 2d*).

Phosphate enters the lake ecosystem mainly through domestic wastewater and agricultural runoff containing fertilizers (Zhao et al., 2021). From *Figure 2e*, TP concentrations were more stable and low during the three years 2017-2019, ranging from 0.010-0.024 mg/L overall, except for September 2019 when the concentration was 0.030 mg/L. Starting in 2020, TP concentrations fluctuated, with lower concentrations in January, April, September, and December of that year and February, March, June,

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and July of the following year < N. D., with concentrations ranging from 0.010-0.030 mg/L in the rest of the months. studying the seasonal characteristics of the concentrations revealed that the characteristics of phosphorus and nitrogen were consistent, with the highest levels of phosphate recorded in summer (mean value 0.017 mg/L) followed by autumn (mean value 0.016 mg/L). This phenomenon is consistent with Lee et al. (2020) who reported higher phosphate concentrations in summer.

The permanganate index reflects the degree of contamination of water bodies by organic pollutants and reduced inorganic substances. *Figure 2f* shows that the permanganate index varied between 0.60 and 2.60 mg/L, with an overall mean value of 1.53 mg/L. The highest value of permanganate index in 2019, with a mean value of 1.90 mg/L, may be due to the decrease in DO concentration in the water column in that year, which resulted in the release of a portion of pollutants from the sediment into the overlying water in an anaerobic environment under the action of microorganisms, making higher COD content in the water column.

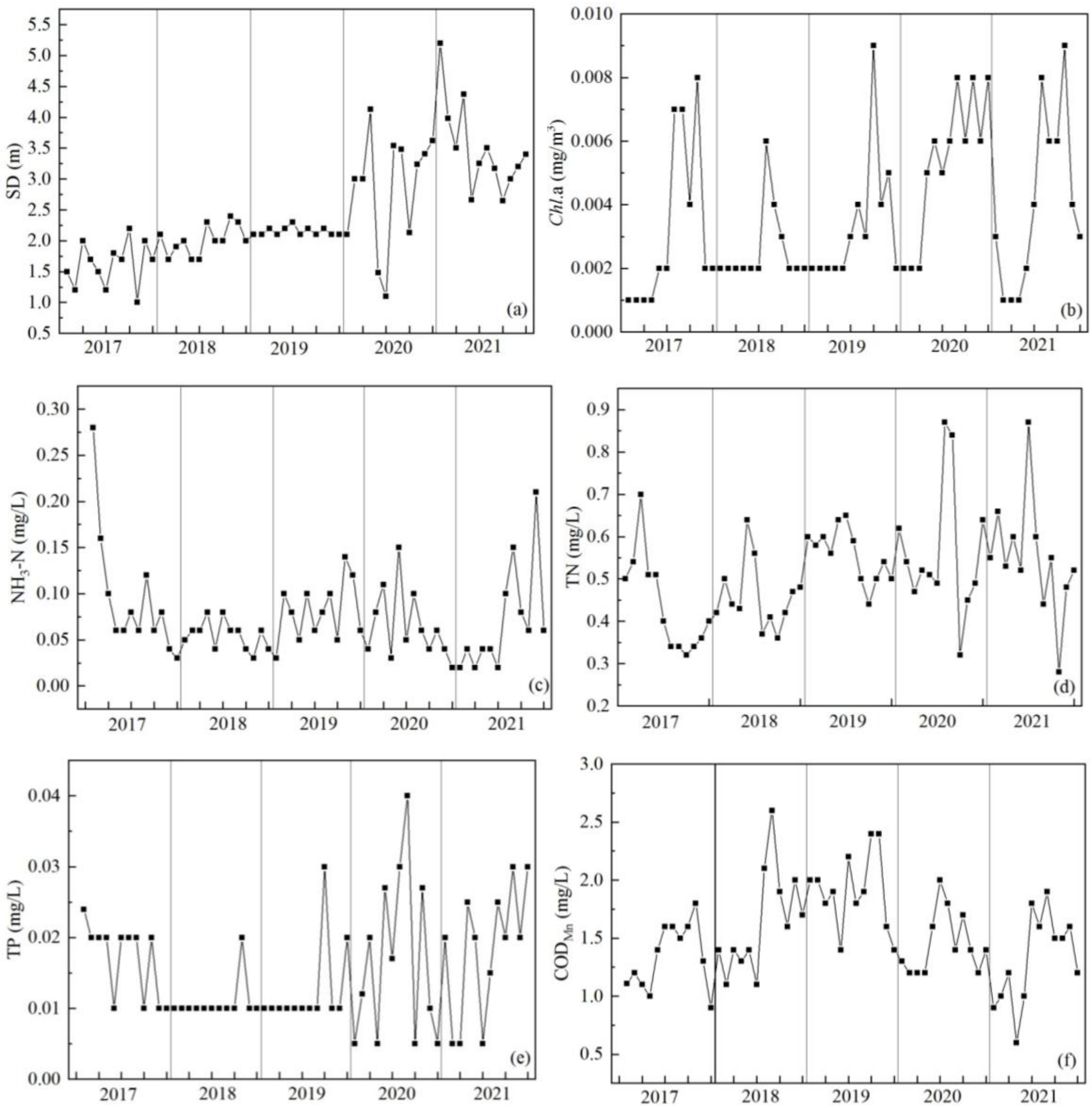

Figure 2. *Time variation characteristics of each water quality index in Shanxi Reservoir*

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The pollution levels of pollutants in the reservoir water bodies are fluctuating, as shown in *Figure 3*. The overall trend of the water pollution index is increasing, with overall values ranging from 0.34 to 0.94, with the index fluctuating in 2020. The extreme values appear in July and August 2020, when the concentration of TP in the water body is high, resulting in the *WPI* values remaining consistent with it. The slope of the fit for the *WPI* was found to be 0.4872, and the pollution index values were proportional to time, with the main body being more influenced by N and P in the water. The average index values for each year since 2017 were 0.52, 0.47, 0.56, 0.57 and 0.58 in order, with no obvious seasonal pattern. The fact that the reservoir water bodies were less polluted in 2018 indicates that the ecologically clean small watershed construction carried out in Shanxi Reservoir in that year was initially effective.

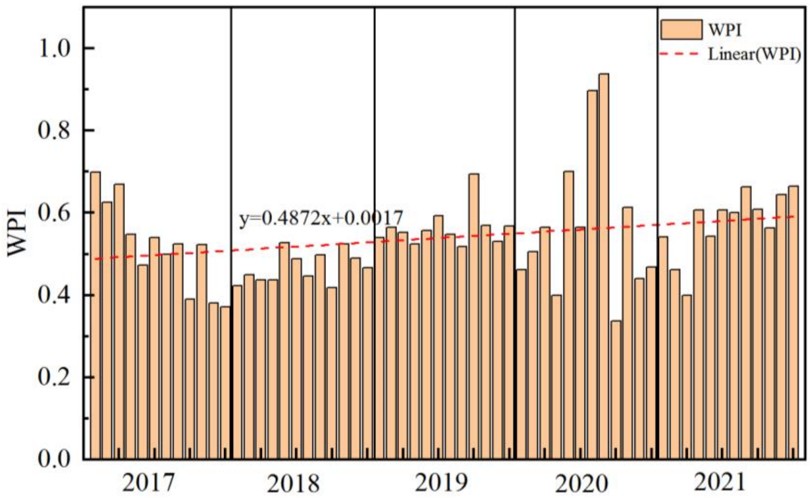

Figure 3. *Results of water pollution index in Shanxi Reservoir from 2017-2021*

Trends in water quality

The Mann–Kendall test method and R/S analysis were used to detect trends in water quality for a total of 60 months during 2017-2021 (*Fig. 4*). The decomposition of this test statistic shows the trend between different variables, including significance level, upward or downward judgment, Hurst index and correlation. The downward trend of water quality can be seen in the statistics of multiple indicators, although the trend characteristics of each variable are very different. Three of the six indicators showed significant trends, with SD, NH_3-N and TN having trend confidence levels above the upper confidence limit of 2.56 ($\alpha = 0.01$), with SD and TN showing upward trends and NH_3 -N showing downward trends. The other three water quality indicators (*Chl*.a, TP, COD_{Mn}) also showed different trends, but did not exceed the significance interval of 1.96. Of these three indicators, *Chl*.a increases and water quality looks worse from this aspect as it can cause eutrophication. COD_{Mn} increases in the period from July 2018 to December 2019 and then starts to decrease in early 2020, indicating that water quality is changing in a way that it is not deteriorating. However, compared to the beginning of the monitoring period, water quality improved significantly in terms of the pollutant being TP.

Therefore, during 2017-2021, the SD and TN of Shanxi reservoir showed a significant increase, *Chl*.a showed an increase but not significant, the overall trend of

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NH_3 -N showed a significant decrease, and TP and COD_{Mn} showed a decreasing but not significant trend. This phenomenon indicates that there is a significant trend of improvement in the degree of organic pollution, phosphorus and NH_3-N, and an increase in the transparency index of the reservoir, which indicates that there are less suspended substances in the water body and the water body is clean.

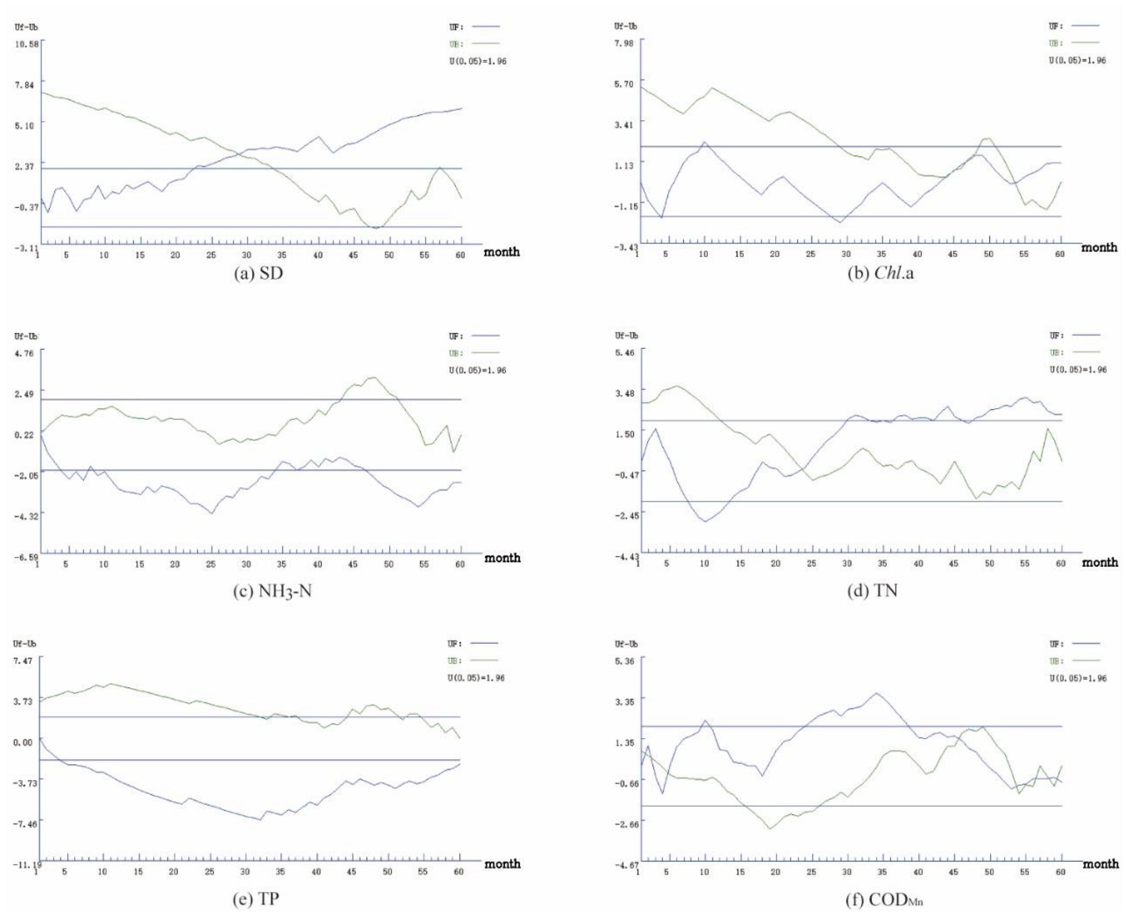

Figure 4. *Trends and change points of different water quality indicators*

The Hurst index derived using rescaled extreme difference analysis shows (*Table 1*) that the relationship between the six indicators and water quality is long-range correlation, which means that the trend of water quality in Shanxi Reservoir in the coming period is consistent with that in 2017-2021. That is, although the concentrations of TN and *Chl*.a have increased, their persistence is weak, and the water quality is not predicted to further deteriorate, but it is still necessary to focus on the TN content in the water to avoid eutrophication of the water body caused by nitrogen pollution, which will harm the water ecology and pollute the drinking water source. Although the trend of *Chl*.a is weakly increasing, the trend of high increase and strong persistence of water transparency can effectively avoid the appearance of black smelly water bodies. As less suspended substances in the water will not lead to the phenomenon of algal outbreak. The decreasing trend of permanganate index showed a strong and continuous trend, and it was inferred that the water quality was improved by organic pollution in the future.

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Table 1. *Results of Mann–Kendall test and R/S analysis in ShanXi Reservoir*

	Mann–Kendall test		**R/S Analysis**		**Future trends in water quality**
	Z	**Trends**	**Hurst index**	**Relevance**	
SD	6.04*	Significant rise	0.86	Strong continuity	Improvements
Chl.a	1.07	Rising but not significant	0.32	Weak persistence	No deterioration
NH_3 -N	-2.57*	Significant decline	0.52	Weak persistence	Improvements
TN	2.68*	Significant rise	0.47	Weak persistence	No deterioration
TP	-1.73	Decline but not significant	0.59	Weak persistence	No deterioration
COD_{Mn}	-0.82	Decline but not significant	0.67	Strong continuity	Improvements

*Representative data showed a significant trend

Water quality change points

In the test results shown in *Table 1* and *Figure 4*, the water quality trend and the point of significant change is designated as the “change point”. In the M-K test, the curve of the positive series UF plotted an upward or downward path. When the value is greater than 0, it means there is an upward trend, otherwise it means no change or a downward trend. When the value exceeds the confidence interval line of ± 1.96, the presence of a significant upward or downward trend can be determined. That is, when the UF and UB curves overlap and intersect, it is the point of change.

In *Figure 4a*, the change point of SD occurs in May 2019. Its value exceeds the confidence zone of 1.96, indicating a significant improvement in water clarity and water quality. UF and UB intersect several times in *Figure 4b*, and there is no significant trend in the change in trend of *Chl*.a. However, after December 2019, maintains its upward trend, so the most plausible point among all intersection points is that period. *Figure 4c* and *4e* show that NH_3 -N and TP have no water quality change points throughout the monitoring process, and the UF of both indicators is below 0, indicating a positive change in water quality. As shown in *Figure 4d*, TN has a clear downward trend from February 2017 to October 2018, and then shows a clear upward trend, with the abrupt change point around the end of 2018. around June 2019, the UF line passes the upper confidence line of 1.96 and finally the Z value reaches 2.68. the UF and UB intersection points of COD_{Mn} are in 2017, 2020 and 2021, respectively appears (*Fig. 4f*), and UF < 0 maintains a downward trend after May 2021 and is similar to the Z-value (-0.82, *Table 1*), so this point is the change point.

Outlook

Adaptation, key pollutants, hydrological processes and pollution degradation were studied according to the trends and characteristics of Shanxi Reservoir. The water quality indicators show the presence of two main types of pollution in the water column: chemical and biological. TN has shown an increasing trend over the last five years of monitoring, and the increasing trend of nitrogen as a growth factor for aquatic organisms provides a measure of algal growth potential and an indicator of the nutrient status of the reservoir. The permanganate index, which reflects the concentration of chemicals and the amount of organic carbon available for bacterial oxidation, has declined, but there is still a need to avoid further organic contamination of the water

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body. Therefore, strict control of pollutants is necessary to protect the quality and safety of water sources.

The following recommendations are made to reduce and remediate pollution. First, the reservoir should strictly enforce surface water environmental quality standards to monitor and prevent pollution of water bodies by rivers and tourism that flow into the reservoir area. Secondly, strict enforcement measures for the public, management and tourists are needed based on the original Class II standards according to the functions and objectives of the water environment in the reservoir area. Third, engineering projects need to be constructed to reduce pollution and prevent the input of additional pollutants. Finally, changes in runoff under climate change need to be considered, and then the water quality needs to be altered according to the natural hydrological cycle using changes in freshwater input. Considering the complexity of water pollution and the availability of various measures in the reservoir area, the following studies can be conducted subsequently, including but not limited to water pollution adaptation measures, key pollutants, hydrological processes, karst spring effects, engineering project implications, and ecological pollution remanagement.

Conclusion

From 2017-2021, the water body of Shanxi Reservoir showed a weak alkalinity overall, with dissolved oxygen concentrations ranging from 6.20-9.31 mg/L and SD values ranging from 1.00-4.37 m. Nitrogen and phosphorus concentrations fluctuated widely, with NH_3 -N concentrations fluctuating between 0.020-0.28 mg/L, with a mean value of 0.073 mg/L; TP concentrations were low in individual months ＜N.D., and the rest were generally between 0.010-0.030 mg/L; permanganate index ranged from 0.60-2.60 mg/L, with a mean value of 1.53 mg/L. The water bodies were heavily polluted by organic pollution in 2019. Due to increased rainfall, pollutants from farming effluent around the reservoir area gushed into the reservoir through surface runoff, resulting in higher NH_3 -N and TP concentrations in summer than in the other three seasons. The water pollution index method shows that the pollution index values in the reservoir area show an increasing trend, with overall values ranging from 0.34 to 0.94.

Water quality trends show that SD and TN are significantly increasing, *Chl*.a is increasing but not significant, NH_3-N overall trend is significantly decreasing, TP and COD_{Mn} shows a decreasing but not significant trend. The water quality has improved to some extent during the monitoring process. The future trend of water quality shows that although NH_3 -N and TP have increased, but with the last five years water quality changes are weak persistence, water quality will not deteriorate, while the value of permanganate index in water will continue to decline, water quality has improved. TN and *Chl*.a concentrations have increased, but its persistence is weak, the prediction of water quality will not further deterioration. *Chl*.a is weakly increasing trend, but high increase and strong. Although the trend of Chl.a was weakly increasing, the high increase and strong persistence of water transparency trend avoided biological pollution to some extent. The decreasing trend of permanganate index showed a strong and continuous trend, and it was inferred that the water quality was improved by organic pollution in the future.

Change points for SD, *Chl*.a, TN and COD_{Mn} occurred in May 2019, December 2019, December 2018 and May 2021, and NH_3-N and TP had no water quality change points throughout the monitoring process.

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