Analysis of Water Quality and Trophic Status of Reservoirs in Chuzhou City, China

Lei Zhang[1], Zijun Zheng[1], Feng Xu[1], Ying Zou[1], Tao Zeng[1], Shuo Li[1], and Shuqi Fang[1]

[1]Chuzhou University

September 19, 2023

Abstract

Reservoir is a vital tool for human utilization of water resources, and the deterioration of its water quality can seriously threaten the water cycle and sustainable urban development. However, there are relatively few studies in academia that analyze and evaluate the water quality of multiple reservoirs at the same time. To address this knowledge deficit, we collected 108 water samples from three different reservoirs in Chuzhou City for 36 months (from 2019 to 2021), explored the drivers of changes in water quality parameters over time and the extent of eutrophication. Our results indicated that the water quality of the reservoirs was deteriorating during the study period, among which Huanglishu Reservoir and Shahe Reservoir reached mild eutrophic status, and both had higher eutrophication levels than Chengxi Reservoir. Secchi Depth (SD), Total Nitrogen (TN), and Total Phosphorus (TP) were the principal factors inducing eutrophication. The biased utilization of reservoir functions was the major contributor to the discrepancy in the degree of eutrophication. Furthermore, Pearson Correlation Analysis revealed that there are significant correlations between many water quality parameters. Cluster Analysis (CA) grouped the 12 months of each year into three clusters (stable water level period, rainy season high flow period, and winter low flow period). Based on this, Analysis of Variance (ANOVA) showed that most water quality parameters varied considerably between the clusters. Collectively, this study identified the actual water quality conditions of three reservoirs in Chuzhou City and provided guidance for local water quality management and environmental protection.

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Lei Zhang[1*], Zijun Zheng[1], Feng Xu[2], Ying Zou[1], Tao Zeng[1], Shuo Li[1], Shuqi Fang[1]

[1]School of Civil Engineering and Architecture, Chuzhou University, Chuzhou, China, 239000.

[2]Chuzhou Ecological Environment Bureau, Chuzhou, China, 239000.

Running title: The analysis and evaluation of water quality in reservoirs

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[*] Corresponding author: Lei Zhang

E-mail: leizhang2014@163.com; Tel. (+86) 0550 3518360; Fax. (+86) 0550 3518360

Address: School of Civil Engineering and Architecture, Chuzhou University, 1 West Huifeng Road, Chuzhou 239000, China.

Abstract: Reservoir is a vital tool for human utilization of water resources, and the deterioration of its water quality can seriously threaten the water cycle and sustainable urban development. However, there are relatively few studies in academia that analyze and evaluate the water quality of multiple reservoirs at the same time. To address this knowledge deficit, we collected 108 water samples from three different reservoirs in Chuzhou City for 36 months (from 2019 to 2021), explored the drivers of changes in water quality parameters over time and the extent of eutrophication. Our results indicated that the water quality of the reservoirs was deteriorating during the study period, among which Huanglishu Reservoir and Shahe Reservoir reached mild eutrophic status, and both had higher eutrophication levels than Chengxi Reservoir. Secchi Depth (SD), Total Nitrogen (TN), and Total Phosphorus (TP) were the principal factors inducing eutrophication. The biased utilization of reservoir functions was the major contributor to the discrepancy in the degree of eutrophication. Furthermore, Pearson Correlation Analysis revealed that there are significant correlations between many water quality parameters. Cluster Analysis (CA) grouped the 12 months of each year into three clusters (stable water level period, rainy season high flow period, and winter low flow period). Based on this, Analysis of Variance (ANOVA) showed that most water quality parameters varied considerably between the clusters. Collectively, this study identified the actual water quality conditions of three reservoirs in Chuzhou City and provided guidance for local water quality management and environmental protection.

Keywords: Chuzhou reservoir; Water quality parameters; Function biased utilization; Trophic level Index

1 Introduction

Water, as the source of life, is a fundamental component of all living organisms and sustains all vital activities in the human body (Sajeev et al., 2020; Westall and Brack, 2018). Nevertheless, the overuse and pollution of water resources by human activities (continuous population growth, rapid progress in agriculture and industry, and high rates of urbanization) have rendered water resources one of the most threatened resources in the world (Varol, 2019). As the important tool for humans to utilize water resources, reservoirs play an extremely prominent role in the agricultural irrigation of rural acres, the living supply of urban residents, the storage project during the drought season, and the flood control project during the rainstorm season (Mamun et al., 2020). However, increased environmental degradation has substantially reduced the role of reservoirs. And under the combined influence of natural and anthropogenic factors (Liu et al., 2022; Paerl and Otten, 2013), causing severe environmental problems of water eutrophication worldwide (Le Moal et al., 2019). When eutrophication occurs in reservoirs, surplus nutrients stimulate the excessive growth of algae, phytoplankton, and other aquatic plants in the water, decreasing DO and increasing Chl-a levels (Li et al., 2021). Currently, the eutrophication of reservoirs has resulted in multiple impacts on ecosystems and social stability (Chen et al., 2020; Mäler, 2000), such as water hypoxia, water bloom, aquatic animal mortality, simplification of food webs, and reduction of biodiversity. According to the studies, eutrophication has occurred in up to 54% of reservoirs in Asia, and its incidence continues to increase (Fink et al., 2018). In conclusion, reservoir eutrophication has been recognized as the most frequent and severe environmental hazard in aquatic ecosystems (Wu et al., 2018).

Proactive gathering of reliable information on changes in water quality for eutrophication management in reservoirs, which has been demonstrated in many countries and regions (Astel et al., 2006; Behmel et al., 2016; Romero et al., 2016). At present, various multivariate statistical analysis techniques are applied in the academic community for multiple and complex data on water quality, such as Cluster Analysis (CA) (Hajigholizadeh and Melesse, 2017), Discriminant Analysis (DA) (Li et al., 2018), Factor Analysis (FA) (Mamun et al., 2021), Principal Component Analysis (PCA) (Zeinalzadeh and Rezaei, 2017), Correlation Analysis (Liu et al., 2010), and Analysis of Variance (ANOVA) (Chen and Lu, 2014), not only do they provide an effective tool for interpreting monitoring data sets, but they also provide significant assistance in identifying the major factors affecting water quality. In addition, the academic community has likewise developed multiple methods for evaluating water quality, examples include the fuzzy mathematical method (Peche and Rodríguez, 2012), gray clustering method (Wong and Hu, 2014), neural network method (Zhou et al., 2020), matter element analysis method (Chen et al., 2012), Water Quality Index (WQI) (Wang et al., 2019), and Trophic level Index (TLI) (Li et al., 2021), they provide an excellent foundation for comprehensively characterizing the degree of eutrophication in reservoirs and for scientifically improving reservoir water quality.

Chuzhou City is located in the eastern part of China's Anhui Province, with a land area of 13,300 km^2, and belongs to the Yangtze and Huaihe River Basin, which is a typical area of the Jianghuai Watershed. The average annual precipitation is 1,035.5mm, and the total water resource is $33.5\times10^8 m^3$, but the per capita water resource is only 908m^3, which is far lower than the national average value of 2,304m^3, and is also lower than the water scarcity warning line of 1,000m^3, which is a water scarcity area. Therefore, sufficient and healthy water resource is particularly essential for the city. The three reservoirs in Chuzhou City (Shahe Reservoir, Huanglishu Reservoir, and Chengxi Reservoir) have been tasked with alleviating water scarcity since their construction. However, as the central lifeblood of the city, the reservoirs have been suffering from eutrophication of water bodies in recent years, which directly or indirectly affects the normal life of the people in the area and the sustainable economic development of the city (Dokulil et al., 2000). Consequently, the evaluation of eutrophication in reservoirs has great significance in providing the scientific basis and control strategies for local water quality management and ecological protection.

Given the limitations of multivariate statistical analysis techniques for water quality assessment when used alone (Chen and Lu, 2014; Güler et al., 2002), in this study, multiple statistical analysis techniques were jointly applied to minimize their limitations and preserve their respective strengths (Chen et al., 2016; Zhou et al., 2007). At the same time, selected a higher scientific basis of the TLI method to analyze and evaluate the trophic state of three reservoirs in Chuzhou City (Liu et al., 2021). Aims: (1) To research the drivers of water quality parameter changes over time in three reservoirs between 2019 and 2021; (2) To evaluate the trophic levels and causes of occurrence in reservoirs using the TLI method; (3) To analyze the differences in nutrient levels in the water bodies of the three reservoirs.

2 Materials and Methods

2.1 Overview of the study area

This study selected Shahe Reservoir (118°07' - 118deg15'E, 32deg20' - 32deg26'N), Huanglishu Reservoir (118deg01' - 118deg07'E, 32deg11' - 32deg16'N), and Chengxi Reservoir (118deg15' - 118deg18'E, 32deg19' - 32deg22'N) as the research objects in Chuzhou City (Fig. 1). Shahe Reservoir is located in Shahe Town, Nanqiao District, Chuzhou City, was built in September 1958, has been reinforced and expanded for five times, reached the current scale in 1979. The reservoir has a catchment area of 300 km^2 and a total capacity of 197 million m^3, as a large (II) type reservoir, it is mainly used for irrigation and has the comprehensive benefits of flood control, urban water supply, aquaculture, and so on. Huanglishu Reservoir is situated in Chuzhou City, Quanjiao County, started construction in September 1959, and in December 1965 was completed. With a control basin area of 262 km^2 and a total reservoir capacity of 315 million m^3, it is a large (II) type reservoir that is mainly used for irrigation, taking into account the comprehensive roles of flood control, water supply, power generation, and aquaculture. Now renamed Biyun Lake, the surrounding area has become very popular for tourism. Chengxi Reservoir lies in the upper reaches of the tributaries of the Qingliu River in Chuzhou City, constructed in 1958 and put into operation in 1965. Reinforcement was carried out in 2010 and is now completed. The control basin area of the reservoir is 168 km^2 and the corresponding capacity is 85.25 million m^3, which has the functions of flood control and security, urban water supply, agricultural irrigation, power generation, and so on. The average annual water supply is about 29 million m^3 to the city and 9 million m^3 to agriculture. It can be clear that guaranteeing the domestic water needs of Chuzhou residents is the major task of the Chengxi Reservoir.

2.2 Sample collection

The water samples in this study were tested from January 2010 to April 2022, and the frequency of testing was three times per month, at the beginning, middle, and end of the month. The study selected the average of the three data as the water sampling data for the month to avoid chance. And most of the water sampling data were collected under clear or cloudy weather, reducing the effect of rainfall. Water samples were collected from three reservoirs in Chuzhou City during the study period, and when the sampling was completed, the water samples were transported to the laboratory in an insulated box with ice packs to test the required indicators. A total of 10 water quality parameters were chosen for reflecting reservoir water quality in the study, which were Water Temperature (WT), pH, Secchi Depth (SD), Dissolved Oxygen (DO), Chemical Oxygen Demand (COD_{Mn}), Biological Oxygen Demand (BOD), Ammonia Nitrogen (NH_3-N), Total Nitrogen (TN), Total Phosphorus (TP), and Chlorophyll a (Chl-a). Among them, WT, pH, and DO were measured *in situ* using a multi-parameter water quality analyzer (YSI 6600V2, USA)., while the remaining parameters were measured by the (Editorial Committee, *Methods of Analysis for Water and Wastewater Monitoring* , State Environmental Protection Administration, 2002). However, when the data were finally selected, it was found that there were large areas of missing data or some key indicators that were not measured in the previous years. Thus the indicator data from 2019 to 2021 were selected as the determining factors for judging the conditions of water quality and the trophic status of the water bodies in three reservoirs in Chuzhou City.

2.3 Trophic assessment

This study used the TLI method for water quality eutrophication evaluation. It is widely used, and the evaluation results have high accuracy, most of the reservoirs in China have chosen this method to evaluate the nutrient status of water quality (Liu et al., 2021) According to *the Technical Provisions on Eutrophication Evaluation Methods and Grading of Reservoirs* developed by the China Environmental Monitoring General Station, taking Chl-a as the benchmark parameter, selecting TP, TN, SD, COD_{Mn} and other parameters with significant correlation with Chl-a to be evaluation factors, and carrying out weighting analysis to get the water quality evaluation results. The following formula is used to calculate the TLI(Σ) value:

$\mathrm{TLI}\,(\Sigma) \;=\; \sum_{j\,=\,1}^{m} Wj \times TLI(j)(1)$

Where TLI(Σ) represents the composite trophic level index, TLI (j) represents the trophic level index of the jth parameter, and Wj is the weight associated with the trophic level index of the jth parameter. Using Chl-a as the base parameter, the normalized correlation weight of the jth parameter is formulated as:

Wj = (2)

Where r_{ij} is the correlation coefficient between the jth parameter and the benchmark parameter Chl-a; m is the number of evaluation parameters. The correlation between Chl-a and other parameters in Chinese reservoirs r_{ij} andr_{ij}^2 (Table 1).

The nutritional status indices for the five indicators were calculated as follows:

TLI (Chl-a) = 10 (2.5+1.086 ln Chl-a) (3)

TLI (TP) = 10 (9.436+1.624 ln TP) (4)

TLI (TN) = 10 (5.453+1.694 ln TN) (5)

TLI (SD) = 10 (5.118 - 1.94 ln SD) (6)

TLI (COD_{Mn}) = 10 (0.109+2.661 ln COD_{Mn}) (7)

Where: the unit of Chl-a is mg/m^3, the unit of SD is m; and the units of other indicators are mg/L.

To illustrate the eutrophic status of the reservoir, a series of consecutive numbers from 0 to 100 was used to grade the trophic status (Table 2) (Li et al., 2021; Wu et al., 2017).

2.4 Statistical analysis and visualization

Before nutrient assessment, 10 water quality indicators were first briefly analyzed over time. Following this, Pearson Correlation Analysis was applied to analyze the correlation between water quality parameters. Afterward, CA and ANOVA grouped the sampling times of the reservoirs into clusters to analyze whether there was variability in the water quality parameters between the clusters. Finally, the TLI method was used to calculate the TLI(Σ) for the three reservoirs and determine the degree of reservoir eutrophication. In this study, the geographic distribution of the reservoirs was drawn through ArcGIS 10.8 software, and each monitoring indicator was statistically and analytically analyzed using SPSS 26.0, and mapping was performed using Origin 2021 software (Liu et al., 2022).

3 Results and Analysis

3.1 Numerical indication of water quality parameters

Based on the annual mean WT values (Fig. S1a), Huanglishu Reservoir (19.03°C) was higher than Shahe Reservoir (18.51°C) and Chengxi Reservoir (18.61°C). All three reservoirs exhibited weakly alkaline environments (Fig. S1b), with Chengxi Reservoir reaching the highest pH value of 8.28, followed by Shahe Reservoir at 8.14, and lastly, Huanglishu Reservoir at 7.98. SD values ranged from 0.40 to 1.79 m (Shahe Reservoir), 0.40 to 1.50 m (Huanglishu Reservoir), and 0.42 to 1.50 m (Chengxi Reservoir), with relatively significant differences (Fig. S1c). DO concentrations were high overall (Fig. S1d), particularly in Chengxi Reservoir (9.26 mg/L), then Shahe Reservoir (9.00 mg/L), and finally Huanglishu Reservoir (8.88 mg/L). The range of COD_{Mn} concentration changes for the three reservoirs was markedly greater in 2020 than in 2019 and 2021 (Fig. S1e). BOD concentrations in Shahe Reservoir and Chengxi Reservoir showed a gradual increase from 2019 to 2021, while Huanglishu Reservoir was not characterized by this change (Fig. S1f). NH_3-N concentrations displayed the biggest range of fluctuations during 2019, which ranged from 0.04 to 0.34 mg/L (Shahe Reservoir), 0.04 to 0.40 mg/L (Huanglishu Reservoir), and 0.04 to 0.39 mg/L (Chengxi Reservoir), respectively, with relatively small ranges of fluctuations in the remaining two years (Fig. S1g). TN concentrations in Chengxi Reservoir decreased annually throughout the study period, whereas the other two reservoirs did not present this feature (Fig. S1h). TP concentrations varied within a narrow range, ranging from 0.01 to 0.05 mg/L in Shahe Reservoir, 0.02 to 0.05 mg/L in Huanglishu Reservoir, and 0.02 to 0.04 mg/L in Chengxi Reservoir (Fig. S1i). Chl-a concentrations were dramatically higher in Shahe Reservoir and Huanglishu Reservoir (4.33 mg/m3 and 4.11 mg/m3) than in Chengxi Reservoir (3.19 mg/m3) during the study period (Fig. S1j).

Based on the monthly average WT values, it was found that three reservoirs showed a changing pattern of high summer (June - August) and low winter (December - February) water temperatures (Fig. S2a). The pH varied more significantly at different times but exceeded 8 most of the time (Fig. S2b). SD changes were not regular and showed instability (Fig. S2c). For example, the maximum mean for both Shahe Reservoir (1.79 m) and Chengxi Reservoir (1.50 m) occurs in April, yet Huanglishu Reservoir presents the minimum monthly mean (0.42 m) in this month. DO concentrations showed a general downward trend from February to October. In addition, the DO levels in Chengxi Reservoir were higher than in the other two reservoirs for a prolonged period (Fig. S2d). COD_{Mn} concentrations in all three reservoirs are characterized by an overall increase followed by a decrease (Fig. S2e). BOD concentrations in Shahe Reservoir and Huanglishu Reservoir peaked at 2.6 mg/L and 3.0 mg/L, respectively, in September, while Chengxi Reservoir peaked at 2.7 mg/L in August of each year (Fig. S2f). Similar to SD, there was no regularity in the variation of NH_3-N concentrations, with Shahe Reservoir and Huanglishu Reservoirs, exhibiting the lowest concentrations in multiple months (Fig. S2g). Regarding the variation of TN concentrations, Shahe Reservoir displayed the maximum average concentration (0.87 mg/L) in October that was higher than that of Huanglishu Reservoir and Chengxi Reservoir (0.78 mg/L and 0.78 mg/L), and Chengxi Reservoir presented the minimum average concentration (0.39 mg/L) in May that was lower than that of Shahe Reservoir and Huanglishu Reservoir (0.54 mg/L and 0.43 mg/L) (Fig. S2h). As for TP, Shahe Reservoir was higher than the other two reservoirs for almost the whole year time, followed by Huanglishu Reservoir, while Chengxi Reservoir was consistently the lowest (Fig. S2i). The Chl-a concentration in Chengxi Reservoir was the lowest nearly all year, with only May and November showing anomalies that were higher than the other two reservoirs (Fig. S2j).

3.2 Correlation Analysis between water quality parameters

The Pearson correlation coefficient matrix was used to test and analyze the 10 indicators common to the three reservoirs (Fig. 2). As expected, there were similar correlations between some of the parameters in the three reservoirs, for example, WT and DO showed a relatively strong negative correlation in Shahe Reservoir ($r = -0.71$, $P < 0.001$) and Huanglishu Reservoir ($r = -0.69$, $P < 0.001$), and a tremendously stronger negative correlation in Chengxi Reservoir ($r = -0.88$, $P < 0.001$). Additionally, WT was also moderately positively correlated with COD_{Mn} in ShaheReservoir ($r = 0.48$, $P < 0.01$) and Huanglishu Reservoir ($r = 0.53$, $P < 0.001$), and highly strongly positively correlated with COD_{Mn} in Chengxi Reservoir ($r = 0.62$, $P < 0.001$).

In the Shahe Reservoir, pH was statistically significantly different from COD_{Mn} (r = 0.41, $P < 0.05$), showing a moderate positive correlation, as well as positively correlating with WT (r = 0.51, $P < 0.01$) and BOD (r = 0.43, $P < 0.01$) at higher confidence levels. In the Huanglishu Reservoir, Chl-a was positively correlated with WT (r = 0.40,$P < 0.01$) and negatively correlated with DO (r = - 0.34, $P < 0.01$). In the Chengxi Reservoir, TP was positively correlated with TN at a confidence level of 0.05 with a correlation coefficient of 0.38, and negatively correlated with pH at a much higher confidence level (r = - 0.44, $P < 0.01$), as well as moderately positively correlated with COD_{Mn} (r = 0.42, $P < 0.01$).

3.3 Cluster Analysis and ANOVA Analysis under the time of water quality parameters

Cluster Analysis (CA) divides the sampling time into clusters depending on similar characteristics of the water quality indicators, which in turn makes an essential contribution to the overall analysis of the water quality later on (Li et al., 2018; Singh et al., 2004; Varol, 2020). In this study, Temporal CA was plotted in a tree diagram based on the changes in 10 metrics for the three reservoirs from 2019 to 2021 (Fig. S3). and clustered the 12 months at (Dlink / Dmax) x 100 < 15. Interestingly, all three reservoirs were categorized into three statistically significant clusters, and the three clusters corresponded closely to the stabilized water level period, rainy season high flow period, and winter low flow period in Chuzhou City, respectively. These two phenomena provide strong evidence of the similarity in the variation of water quality indicators in the three reservoirs. ANOVA results confirmed significant differences between clusters. For example, all water quality parameters except SD, BOD, NH_3-N, and TP in the Shahe Reservoir showed significant differences ($P < 0.05$) between clusters (Table 3), for Huanglishu Reservoir, WT, pH, and DO were excluded (Table 4); and compared to the Shahe Reservoir, the Chengxi Reservoir contains more NH_3-N and TP (Table 5).

3.4 Eutrophication of reservoir water quality

Through using the TLI method to derive the TLI (Σ) value of each reservoir, we found that the eutrophication level of Huanglishu Reservoir was the most serious during the three years, followed by Shahe Reservoir, and optimal for Chengxi Reservoir. The highest value of TLI(Σ) in the Huanglishu Reservoir was 52.38 and the lowest value was 40.40, the water body was medium nutrition most of the time, but there existed three periods of time when the TLI(Σ) was greater than 50, which was in the mild eutrophication status. This result indicates that the water quality of the Huanglishu Reservoir has been mildly polluted. The eutrophication evaluation results of the water body in Shahe Reservoir are similar to the Huanglishu Reservoir, with the fluctuation range of TLI(Σ) from 40.96 to 51.29, and the water quality evaluation level is mild eutrophication only in October 2020, and the TLI(Σ) tends to be close to 50 in most of the other periods, which is on the edge of the medium nutrient water quality. The TLI (Σ) value of Chengxi Reservoir was always below 50, which did not reach the criterion of mild eutrophication, and the qualitative evaluation of the water body was good, the results indicated that the water body of the reservoir was lightly polluted. As a whole, the water quality class of Huanglishu Reservoir and Shahe Reservoir reached Class III, whereas Chengxi Reservoir was always maintained at Class II (Fig. 3 and Table 1).

3.4.1 Annual changes

The TLI(Σ) of the three reservoirs showed large differences between years (Fig. S4). The annual mean TLI(Σ) values of Huanglishu Reservoir varied in a wide range from 2019 to 2021 (43.92 46.68), followed by Shahe Reservoir (41.39 43.10), while there was almost no change in Chengxi Reservoir (44.84 45.39). Furthermore, the annual average TLI(Σ) values in Shahe Reservoir are generally lower than those in Huanglishu Reservoir and Chengxi Reservoir, with relatively good water quality. Interestingly, the annual average TLI(Σ) values of all three reservoirs exhibited maximum values in 2020 and minimum values in 2019, with the TLI(Σ) of Huanglishu Reservoir (50.21 43.1) exceeding 50 in 2020, and the nutrient status of the water body was mildly eutrophic in that year, with a water quality level of Class III (Table 1), while none of the other reservoirs reach this standard.

3.4.2 Monthly changes

Similar to the annual variation (Fig. S5), the monthly mean TLI(Σ) values of both Shahe Reservoir and

Chengxi Reservoir varied over a wide range (41.80 48.85 and 39.20 45.35), whereas those of Huanglishu Reservoir varied over a smaller range (43.43 47.35). The maximum monthly mean TLI(Σ) values generally occurred from August to October, the minimum TLI(Σ) values generally occurred from April to June, as well as all three reservoirs showed a very clear upward trend from June to August (summer months), probably due to the effect of temperature on algae. This phenomenon indirectly confirms that temperature is one of the causes that influence changes in the eutrophication of water bodies (Herb and Stefan, 2003). Besides, through the comparison, it was found that the TLI(Σ) value of Chengxi Reservoir was lower than that of Huanglishu Reservoir and Shahe Reservoir in all the months, and it can also be concluded that the water quality of Chengxi Reservoir is better than that of Huanglishu Reservoir and Shahe Reservoir.

4 Discussion

4.1 Analysis of drivers of water quality parameters over time

Consistent with previous studies, the influence of natural and anthropogenic factors plays an irreplaceable role in the process of changing water quality parameters in reservoirs (Dodds and Cole, 2007; Wang et al., 2020).

Because of differences in natural geographic location, there is some variability in WT changes among the three reservoirs. Huanglishu Reservoir is located in Chuzhou on the border with Hefei City and Maanshan City, as well as geographically situated to the south, with higher temperatures and greater exchange of heat in the atmospheric cycle. As a result, Huanglishu Reservoir has the highest water temperatures. Shahe Reservoir is in a populated area, where air circulation is difficult, heat dissipation is weak, for relatively high water temperatures. Chengxi Reservoir borders Mt. Langya and is surrounded by large vegetation cover, with less solar radiation absorbed by the ground, leading to the lowest water temperatures. As shown by Pearson Correlation Analysis, WT showed significant correlations ($P < 0.01$ or $P < 0.001$) with pH, DO, COD_{Mn}, TP, and Chl-a (Fig. 2). Lower WT reduces the rate of planktonic algal blooms, thereby slowing their ability to consume DO (Varol et al., 2012; Naveedullah et al., 2016). This is the primary explanation for the higher DO concentrations in the Chengxi Reservoir than in the other two reservoirs. Appropriate WT increases phytoplankton abundance in the reservoir, enhances photosynthesis, and reduces CO_2, ultimately resulting in higher water pH (Wu et al., 2014). Moreover, the Chengxi Reservoir has the highest phytoplankton population in its own right and hence with a higher pH than the other two reservoirs. It is well known that the biological oxidative decomposition of COD_{Mn} needs to consume a large amount of DO, however, Excessive WT causes planktonic algae to preemptively deplete DO, which in turn alters the COD_{Mn} concentration (Yin et al., 2011). Furthermore, ANOVA showed that $COD_{Mn}$was remarkably different ($P < 0.05$) between clusters (Tables 3 to 5), which may be related to the occurrence of water bloom in the reservoirs. During the outbreak of blooms, phytoplankton will rapidly multiply and die, generating large amounts of organic matter and causing elevated COD_{Mn} concentrations in reservoirs (Klemas, 2012; Smayda, 2008).

Under anthropogenic interference, the elevated discharge of industrial wastewater and the rise in agricultural fertilizers and livestock manure have to a large extent contributed to the enrichment of reservoir waters with large quantities of organic matter and inorganic salts, which has led to an increase in the concentration of BOD (Liu et al., 2022). Of these, the area surrounded by Huanglishu Reservoir is mostly villages and towns, with relatively backward industrial and agricultural technology and slow development. Therefore, the reservoir does not present the characteristic. As everyone knows, the removal of nitrogen sources mainly relies on nitrification under aerobic conditions and denitrification under anaerobic conditions (Ma et al., 2016; Zhou and Hosomi, 2008). However, when the water environment is polluted by humans, the water DO is no longer stabilized and both effects are repulsive, resulting in the accumulation of NH_3-N and TN from factory effluents and municipal wastewater discharges (Yao et al., 2011). Owing to the higher DO concentrations in Chengxi Reservoir, the nitrogen source concentrations (TN and NH_3-N) for water quality are lower than the other two reservoirs. As for the variation of TP concentrations, all three reservoirs characterized by higher concentrations in spring and summer (March to August) than in fall and winter (September to December). That is primarily attributed to the fact that the former period is a busy farming season, agricultural cultivation requires the use of large quantities of phosphorus fertilizers, which, after being dissolved by rainfall, sink into the reservoirs along with pollutants enriched with highly concentrated sources of phosphorus, ultimately resulting in higher TP concentrations than in the latter period (Kim et al., 2001). Chl-a can reflect the growth of phytoplankton in water (Wurtsbaugh et al., 2019). As revealed by the TLI method, the eutrophication level of the Huanglishu Reservoir and the Shahe Reservoir was higher than Chengxi Reservoir (Fig. 6 and Table 2). The former two reservoirs would receive more inputs of exogenous nutrients, phytoplankton biomass can be dramatically boosted. Hence, it was relatively easy to increase the Chl-a concentration. (Saluja and Garg, 2017).

Certainly, natural and anthropogenic factors can simultaneously affect water quality parameters. The irregularity exhibited by the parameter SD over time is mainly related to the erratic rainfall in the area and the irregular water demand of the population. There is less small-scale vegetation along the reservoir, large amounts of sediment are easily washed into the reservoir by rainwater, impeding light penetration and causing changes in SD. The water demand of the local population can lead to irregular opening and releasing of the reservoir, which greatly affects the stabilization of the phytoplankton population in the reservoir. Excess phytoplankton can green the water and reduce the SD of the water body (Sommaruga and Augustin, 2006). Moreover, the different light intensities under sunny and cloudy days are another important factor contributing to the erratic SD variation. Again, because of the difference in reservoir eutrophication, clean water quality is less likely to experience algal overgrowth and does not easily prevent light from penetrating the water layer (Guo et al., 2022), thus SD changes are more stable in Chengxi Reservoir.

4.2 Reservoir water quality eutrophication studies

Through evaluating the TLIs of five parameters of water quality in three reservoirs in Chuzhou City (Figs. S6 to S9), the results demonstrated that the dominant factors causing eutrophication in the three reservoirs were SD, TN, and TP. The mechanism of its occurrence is mainly when the water body is enriched with excessive N, P nutrient salts, algae will rapidly multiply and form water bloom, which hinders the penetration of light, thus leading to the eutrophication of the water body. Meanwhile, TN and TP have historically been recognized as the main drivers of eutrophication (Havens and Walker, 2002; Sui et al., 2022), this is also consistent with the findings of this study. In summary, water quality in the three reservoirs is generally poor, and the TLI (Σ) does not show a sustained downward trend (Figs. S4 and S5). Consequently, it is still imperative to continuously assess the eutrophication of the three reservoirs in Chuzhou City in the future.

The TLI (SD) was the highest in the evaluation of the trophic status of the reservoir water quality (Fig. S6). This is due to Chuzhou City belonging to the subtropical monsoon climate, long-term seasonal winds will be around the reservoir area of sediment, rocks plant debris, etc., blown into the reservoir, resulting in a gradual accumulation of suspended particles in the water, the refraction effect becomes stronger and stronger, and ultimately impede the penetration of light, greatly improving the TLI (SD) (Saluja and Garg, 2017). Moreover, the pigmented substances secreted by some microorganisms and aquatic plants in reservoirs can also affect water transparency and change the TLI (SD), such as chlorophyll and carotenoids from algae (Qi et al., 2014). The three reservoirs had higher TLI (TN) and TLI (TP) in 2019 than in 2020 and 2021 (Fig. S6), which was primarily attributed to human activities. Throughout nearly all of 2019, industry, agriculture, and commerce have functioned normally in Chuzhou City, with large population movements, giving rise to high levels of eutrophication in the reservoir. However, in 2020 and 2021, when China is experiencing the severity of COVID-19, many businesses have ceased operations and population activity has decreased dramatically, resulting in a downward trend in the nutrient indicators (TN and TP) in water bodies. Among the reservoirs, the TLI (TN) of Shahe Reservoir was abnormal in 2021, mainly because of the better management of the epidemic in the area around the reservoir and the return of population activities to the pre-epidemic period (Liu et al., 2021), thus the eutrophication of the reservoir was again aggravated.

Although the values of TLI (COD_{Mn}) and TLI (Chl-a) were relatively low, it does not mean that COD_{Mn} and Chl-a do not contribute to the occurrence of eutrophication in the reservoir. Algal overgrowth triggered by COD_{Mn} pollution and water blooms caused by high Chl-a concentrations can greatly help improve the reservoir trophic state (Du et al., 2019). In monthly variation, the TLI (COD_{Mn}) in all three reservoirs reached a maximum around September and a minimum around April (Figs. S7 to S9), it is primarily related to the storage and drainage functions of the Chuzhou City Reservoir. COD_{Mn} is a commonly used indicator of water pollution by organic matter (Li et al., 2018). Reservoir impoundment in September increases the release of organic pollutants from inundated soils and plants, intensifying the nutrient levels in the water body, whereas reservoir dewatering in April causes the opposite result (Zhao et al., 2013). It is well known that Chl-a is an essential indicator for characterizing algae biovolume and measuring the degree of eutrophication. (Li et al., 2021; Saluja and Garg, 2017; Sui et al., 2022). The TLI (Chl-a) from May to September was higher than that of other months (Figs. S7 to S9), mainly because the summer temperature is suitable for phytoplankton growth and reproduction, which promotes the metabolic rate and cell division of phytoplankton, increases the productivity of phytoplankton, and aggravates the eutrophication of the water body. Of these, the anomalies in the Shahe Reservoir and Chengxi Reservoir in November can only be attributed to the input of N and P nutrients and pollutants that were far greater in that month than in other months, which promoted algal growth and led to a rapid increase in Chl-a concentrations.

From the CA results, it can be seen that there is a cluster corresponding to the winter low-flow period in all three reservoirs (Fig. S3), and the TLI(j) of the five parameters is higher during this period than the time corresponding to the other two clusters, which strongly suggests that low precipitation is an important reason for the high probability of eutrophication in the reservoirs. That's because low precipitation during this period can lead to slow flow and poor exchange in the reservoir, which is extremely likely to contribute to algal growth and thus increase the nutrient status of the water body. (Liu et al., 2021).

4.3 The reasons for the differences in the eutrophication level of the three reservoirs in Chuzhou City

According to the CA method, the sampling time groups of all three reservoirs were divided into three statistically significant clusters, primarily because the three reservoirs belong to the same city of Chuzhou, have the same geographic characteristics, and natural background, and are influenced by similar natural environments and human activities. However, in this case, three reservoirs did not show a consistent degree of eutrophication. The eutrophication degree of Shahe Reservoir and Huanglishu Reservoir was significantly higher than that of Chengxi Reservoir, both in the course of the annual change (Fig. S4) and the monthly change (Fig. S5). The reason for this is mostly due to the biased utilization of reservoir functions by the region. Shahe Reservoir is a large reservoir with comprehensive benefits in Chuzhou City, which not only serves as an important local aquaculture site but also undertakes irrigation and water supply for neighboring agriculture. Among that, aquaculture often requires abundant imported food and feed, which is highly susceptible to imbalances in N concentrations in the water body (Zhou et al., 2011). The average TN concentration in the reservoir reached 0.98 mg/L in November, which already belongs to Class III water ([?]1.00 mg/L) in China's environmental quality standard for surface water (GB3838-2002). Not only that, the secretions and excretions produced by fish and shrimp contain a large number of nutrients, which are dispersed from the nets or suspended or deposited at the bottom of the reservoir, greatly increasing the P concentration in the water body. TP concentrations in Shahe Reservoir reached 0.05 mg/L in multiple months and were notably higher than those in Huanglishu Reservoir and Chengxi Reservoir. It was pointed out that the discharge from farmed fish accounted for 10 - 20% of the total phosphorus load in some reservoirs and had a much larger actual impact on eutrophication than other sources of phosphorus (Zhou et al., 2011). Besides, the agricultural development around the Shahe Reservoir has been using chemical fertilizers for a long time. After being irrigated by the Reservoir, the chemical fertilizers will be completely dissolved, and the nutrients in its composition will slowly flow into the Reservoir, which will ultimately cause the N and P content of the water body to exceed the standard, and aggravate the eutrophication of the Reservoir. It is worrying that the chemical fertilizer application rate has been increasing to date (Kim et al., 2001). Huanglishu Reservoir also serves as a comprehensive reservoir that not only has the two functions of the Shahe Reservoir mentioned above, but also has the title of a 4A-level scenic area. After being renamed Biyun Lake, it became a famous tourist resort in Quanjiao County, Anhui Province, attracting countless tourists, which has become an important cause of the serious eutrophication of the water body. It is well known that human activities contribute significantly to the occurrence of eutrophication in reservoir waters (Huang et al., 2014). With the rise in the number of tourists, the amount of domestic sewage discharged from scenic tourist areas has increased dramatically, and the water bodies are prone to enrich a large number of highly concentrated nutrients, which in turn causes eutrophication in the reservoirs (Le et al., 2010). COD_{Mn} can indicate the extent of organic pollution in water bodies (Li et al., 2018). As expected, Huanglishu Reservoir exceeded the remaining two reservoirs in average COD_{Mn}concentrations each year. Although Chengxi Reservoir has multiple functions, its main function is to undertake the water supply needs of the residents of Chuzhou City, and other functions only play a role in a small number of areas. This is the important reason why the eutrophication level of Chengxi Reservoir is the lowest. According to the TLI method, the concentrations of all five indicators in Chengxi Reservoir are more reasonable and stable than the other two reservoirs. The degree of eutrophication in Huanglishu Reservoir is slightly higher than that in Shahe Reservoir (Fig. 3), due in large part to the fact that the Huanglishu Reservoir is much older and more severely aged, resulting in slower water movement and decreased self - purification capacity (Holz et al., 1997), which affects the degree of eutrophication in the reservoir.

5 Conclusion

The study based on the numerical changes of 10 water quality parameters in three reservoirs in Chuzhou City from 2019 to 2021, analyzed the drivers of water quality parameters in the reservoirs over time, and comprehensively evaluated the key factors responsible for the occurrence of eutrophication in the reservoirs and the reasons for the discrepancy in the trophic status of the three reservoirs. The results show that the water quality of all three reservoirs is polluted under the impact of the natural environment and anthropogenic activities. According to the TLI method, we concluded that the water quality parameters contributing more to the occurrence of eutrophication were SD, TN, and TP. A plausible explanation for this is that when a water body is enriched with too many N and P nutrients, algae will rapidly multiply, forming water blooms and blocking light penetration, leading to eutrophication. The biased utilization of reservoir functions is the major factor contributing to the differences in the trophic status of the three reservoirs. Furthermore, eutrophication levels in the three reservoirs never showed significant signs of abatement from 2019 to 2021. Therefore, the study still needs a long time to analyze and evaluate the eutrophication of Shahe Reservoir, Huanglishu Reservoir, and Chengxi Reservoir in Chuzhou City, so as to propose a management plan for improving the water quality and reducing the nutrient index, and to ensure that the water quality of the reservoirs continues to be good.

Acknowledgements

This work was supported by the Science Research Project in Universities of Anhui Province for Distinguished Young Scholars (2022AH020070), the Top-notch Scholarship Program in Universities of Anhui Province (gxbjZD2022071), the Major University Science Research Project of Anhui Province (KJ2021ZD0132) and the Science Research Project of Chuzhou University (2022XJZD05; zrjz2021001).

CRediT authorship contribution statement

Lei Zhang: Conceptualization, Software, Resources, Funding acquisition; **Zijun Zheng:** Data Curation, Writing - Original Draft, Supervision; **Feng Xu:** Investigation, Resources, Project administration;**Ying Zou:** Software, Formal analysis, Validation;**Tao Zeng:** Software, Formal analysis, Supervision; **Shuo Li:** Methodology, Data visualization; **Shuqi Fang:** Software, Data visualization, Surveys.

The authors declare that they have no conflicts of interest.

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Highlights

- Combined use of various statistical analysis techniques.
- Multiple parameters jointly determined water quality status.
- SD, TN, and TP are the main factors inducing eutrophication.
- Biased utilization of reservoir functions causes water quality differences.

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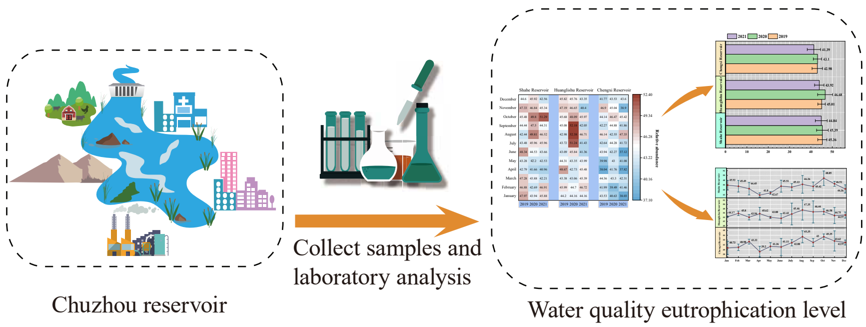

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