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Eutrophication Risk Assessment of Tributaries in the Three Gorges Reservoir: A Case Study of the Pengxi River

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ABSTRACT. Evaluating the eutrophication risk in reservoir areas is very important for environmental protection. However, the periodic backflow of water in reservoir areas makes evaluating the eutrophication of tributaries in reservoir areas more difficult. In this study, based on the basic principle of the copula function, combined with the water environment simulation results of the Pengxi River, a tributary of the Three Gorges Reservoir, a new perspective for considering the interaction between water environment variables was proposed to evaluate the joint eutrophication risk probability. The results showed that the fluidity of the whole Pengxi River was poor, which was conducive to the deposition and enrichment of pollutants. The total nitrogen (TN) in Hanfeng Lake and the main stream of the Pengxi River was always above the level of moderate eutrophication, while total phosphorus (TP) varied over a large range, from mesotrophic to hyper-eutrophic. In 2021, the joint risk probability of TP and TN was the highest, at 45%, when they were both hyper-eutrophic in Hanfeng Lake. When TP was slightly eutrophic and TN was moderately eutrophic, the joint risk probability was the highest in Pengxi River, at 42%. The relatively clean water of the Yangtze River flowing back into the Pengxi River reduces its eutrophication risk. The results of this study provide a scientific basis for the prevention and control of water eutrophication in the Three Gorges Reservoir.

Keywords: eutrophication risk, three gorges reservoir, water quality, backflow, joint probability

1. Introduction

Eutrophication in lakes and reservoirs is a serious problem worldwide, including in the Erhai Lake in China (Lin et al., 2021), the Great Lakes in the United States (Van Meter et al., 2020), and Hearnes Lake in Australia (Conrad et al., 2019). Eutrophication destroys the ecosystem balance and restricts water availability for drinking, irrigation, and leisure (Pernet-Coudrier et al., 2012; Xu et al., 2019; Strokal et al., 2020). Recently, the demand for domestic and industrial water, as well as water for power generation, have led to many reservoir projects being undertaken around the world, including the Three Gorges Reservoir in China (Ran et al., 2019) and the Tenkiller Reservoir in the United States. The reservoir impoundment operation transforms a flowing river into a deep-water reservoir (Zajac et al., 2017), extending the water retention time and making it easier for nutrients, such as total nitrogen (TN) and total phosphorus (TP), to accumulate in reservoirs than in natural rivers, thus increasing the eutrophication risk in the reservoir area (Liu et al., 2012; He et al., 2018). In addition, the periodical fluctuation of the water level in the reservoir area may cause pollutants from the main stream to flow backwards into tributaries, thus aggravating the eutrophication risk (Ran et al., 2010). Therefore, evaluating the eutrophication risk in reservoir areas is of great significance.

The eutrophication evaluation of a water mainly uses the corresponding evaluation methods to determine the nutrition level to explain the eutrophication degree of the water body (Zeng et al., 2016). Many scholars use the single factor index, principal component analysis, and comprehensive water quality index identification methods to evaluate the eutrophication risk, but there is a lack of research on the joint risk probability of multiple eutrophication indicators (Liao et al., 2019; Zhang et al., 2021; Zang et al., 2022). However, previous studies do not emphasize the correlation between different water quality indicators (Vinçon-Leite and Casenave, 2019), and few studies have focused on the joint risk probability of different indicators (Schumann, 2017), thus reducing the accuracy of their assessments. Therefore, it is necessary to consider the joint influence of multiple water quality indicators to improve the accuracy of eutrophication risk assessment. The copula model is a method used to study the probability of multivariate joint distribution. It does not limit the types of marginal probability and is easy to expand to multiple dimensions, allowing for the flexible construction of multi-dimensional joint distributions. Because of its diverse

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forms and flexible use, it is widely used in hydrology, climatology, and flood risk analysis, and has great application potential in water quality risk analysis (Sadegh et al., 2017; AghaKouchak et al., 2020). In copula theory, the matching degree between the factual observation data and the selected marginal distribution function is vital for the accuracy of the copula joint probability distribution model (Lee, 2018). However, the monthly observation data is usually insufficient, which reduces the model's accuracy. Therefore, the annual simulation results of the mathematical model were used to better fit the marginal distribution in this study.

As the largest reservoir project in China, the Three Gorges Reservoir has yielded significant benefits, such as flood control, hydropower generation, and navigation (Li et al., 2021). However, the impounding reduces the flow velocity and self-purification capabilities of the reservoir area, and algal blooms occur frequently in the backwater areas of some tributaries, which threaten the water environment safety of the reservoir area (Wang et al., 2012; Zhao et al., 2016; Long et al., 2020). Currently, the research on eutrophication in the Three Gorges Reservoir mainly focuses on eutrophication status, evaluation, prediction, mechanisms, and control measures, as well as on algae community structure and nutrient concentrations (Huang et al., 2016). For example, Liu et al. (2016) believed that the triggering of algal blooms depends on the relationship between the mixing depth and euphotic depth; Zhou et al. (2011) analyzed the phytoplankton species composition and biomass in Xiangxi River through field investigation and obtained the relationship between algae growth and environmental factors; Lian et al. (2014) put forward algae control measures for ecological reservoir operation through a hydrodynamic water quality model; and Wu et al. (2017) proposed a data-driven model based on semi-supervised classification to evaluate the degree of eutrophication in the Three Gorges Reservoir. Few scholars have analyzed the risk probability of eutrophication in the Three Gorges Reservoir from the perspective of risk, so evaluating the eutrophication risk in the Three Gorges Reservoir is of great significance.

The purpose of this study was to evaluate the eutrophication risk in the Three Gorges Reservoir from a new perspective by considering the joint influence of multiple water quality indicators. In this study, the Pengxi River, a tributary of the Three Gorges Reservoir with a complex environment of "reservoir dam", was taken as the research object and the hydrodynamic and water quality model was used to study the water environment change characteristics of this unique river. By constructing a copula model, the joint eutrophication risk of the TN and TP indexes in the Pengxi River was studied. This study not only makes up for the deficiency of previous studies on eutrophication risk probability in the Three Gorges Reservoir, but also helps to understand the water environment characteristics of water bodies with various morphological characteristics such as rivers, lakes, and backflow bays, and provides a scientific basis for the prevention and control of eutrophication in the Three Gorges Reservoir (Ji et al., 2017; Gao et al., 2018; Li et al., 2021).

2. Materials and Methods

2.1. Study Area

The Pengxi River (107°56′ ~ 108°54′ E and 30°49′ ~ 31°42′ N), located at the eastern edge of Sichuan Basin, has a drainage area of 5,173 km^2 and a total length of 182.4 km and is the largest tributary in the northern bank region of Three Gorges Reservoir. Following the completion of the Three Gorges Reservoir, the total area of the Pengxi River water-level fluctuation zone is 65 km^2, which is the largest water-level fluctuation zone in the middle reaches of the Three Gorges Reservoir, accounting for 19% of the total water-level fluctuation zone in the Three Gorges Reservoir (Zhu et al., 2020). In order to reduce the adverse impact of the water-level fluctuation belt, a water-level regulating dam was built in the Wuyang, Kaixian County, forming a lake with an area of 14.8 km^2, and the Hanfeng Lake Basin with the Wuyang water-level regulating dam as the control node was formally formed (Johnson and Rainey, 2012; Li et al., 2021; Sun et al., 2021). The Wuyang regulating dam is the only dam in the three Gorges Reservoir, and it forms a miniature model of the three Gorges reservoir. Therefore, the Pengxi River has become a region with unique geographical conditions, the largest area of the fluctuating zone, and the most typical hydrological conditions in the entire Three Gorges Reservoir. It is of great academic value to study the water environment of the Pengxi River backflow area (Sun et al., 2010, 2012). The study area is shown in Figure 1.

2.2. Numerical Model

Affected by the impoundment of the Three Gorges, the Pengxi River has a large surface area and uneven spatial distribution. Considering that the water quality of the Pengxi River is slightly different in different water depths, the initial conditions, boundary conditions and calibration data are the average values of the monitoring data of the upper, middle and lower layers. Therefore, from the point of view of reflecting the overall change characteristics of water flow and water quality in the study area and meeting the actual demand, a two-dimensional mathematical equation based on the average water depth was adopted to describe the movement characteristics of the water flow and water quality. Based on the MIKE21 model (Jia et al., 2018; Ahn et al., 2019), the hydrodynamic and water environment models of the Pengxi River Basin were established in this study.

2.3. Risk Model

Eutrophication is a comprehensive representation of water quality deterioration, and its evaluation index therefore usually consists of several key indicators. Therefore, the risk probability of water eutrophication should be different based on the combination of risk probabilities when the key indicators exceed the standard limits. In this study, the eutrophication risk of the Pengxi River was characterized by the joint probability value of the TN and TP indicators. In other words, the risk level of eutrophication was the joint probability when the TN concentration exceeded a certain value ($> X_1$) and the TP concentration

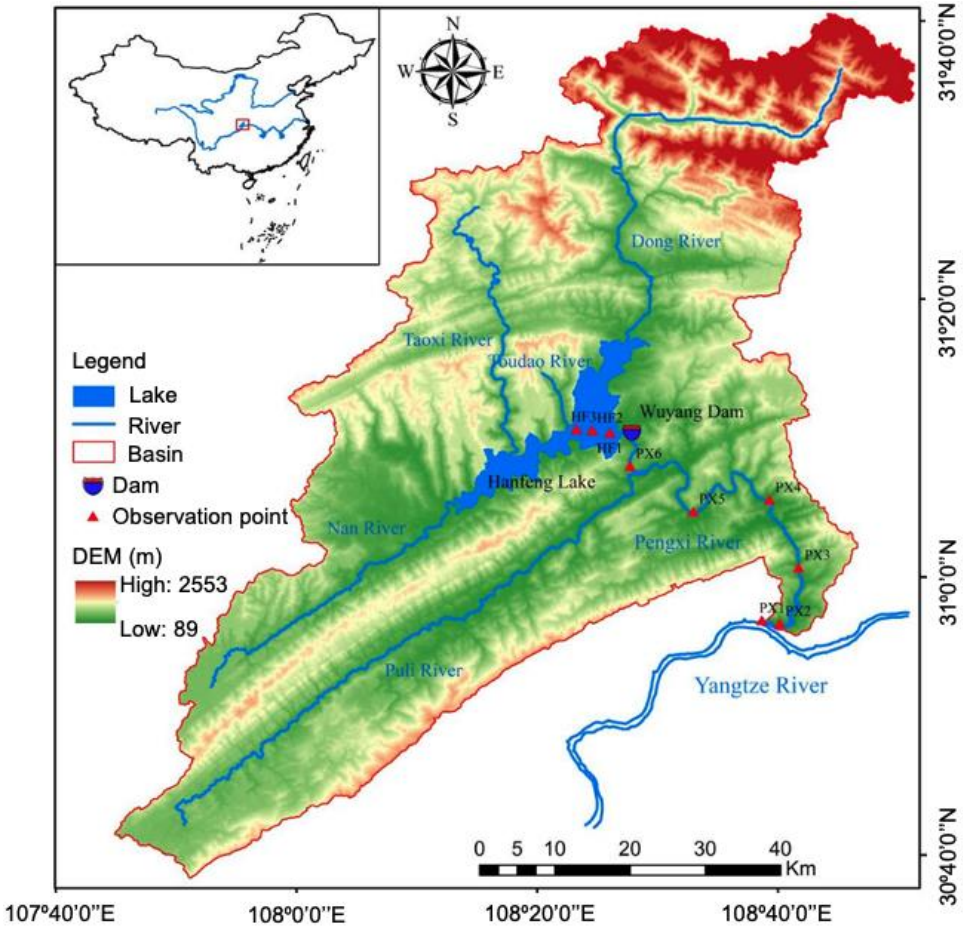

Figure 1. Study area (water quality monitoring sites: PX1-Estuary, PX2-Shuangjiang Bridge, PX3-Huangshi, PX4-Gaoyang, PX5-Yanglu, PX6-Qukou, HF1-front of the dam, HF2-reservoir center, and HF3-reservoir tail).

Table 1. Limiting Value of the Nutrient Level for the Water Quality Index of the Lake

Index	Oligotrophic	Mesotrophic	Slightly eutrophic	Moderately eutrophic	Hyper-eutrophic
TP / (mg/L) ≤	0.005	0.05	0.1	0.2	1.3
TN / (mg/L) ≤	0.050	0.50	0.8	2.0	14.0

exceeded a certain value (> Y_1). X_1 and Y_1 are the limits of the nutritional status grading standards corresponding to the TN and TP of lakes in China (Table 1).

2.3.1. Marginal Probability Distributions

According to the simulation results of the Pengxi River water environment model, the annual simulation sequences $\{x_n \mid n = 1, 2, ..., N\}$ of HF1 to HF3 and PX1 to PX4 points were extracted, where n is the number of simulation sequences. For any sample value x_m in the simulation sequence $\{x_n\}$, if the number less than x_m in the simulation sequence $\{x_n\}$ is N_m, then the cumulative percentage corresponding to x_m can be expressed as:

$$P(x_m) = P(x_i \le x_m) = \frac{N_m}{N} \quad (1)$$

where x_i is a water quality monitoring index; $P(x_m)$ is the frequency function of the event $x_i \le x_m$. The frequencies of all sample values in the simulation sequence $\{x_n\}$ can be calculated to obtain the frequency marginal probability curve of the simulation sequence $\{x_n\}$.

2.3.2. Joint Probability Distribution

Copula theory, as mentioned, was introduced to consider the correlation between TN concentration and TP concentration. Use of this theory can connect the edge distribution of many different variables into a joint probability distribution function (Daneshkhah et al., 2016). According to the Sklar theorem, for a two-dimensional joint distribution function $H(x,y)$ with continuous marginal probability functions U and V, there is a unique two-dimensional copula function C, so that $H(x, y) = C(u, v)$.

Assume that X and Y represent interrelated index sequences in water eutrophication events, and their marginal distribution functions are u and v, respectively. The expression of their

two-dimensional joint distribution probability is as follows:

$$F_{UV}(u,v)=P(X\le x,Y\le y)=\int_{-\infty}^{u}\int_{-\infty}^{v}f(u,v)dudv=C(u,v) \quad (2)$$

When both indexes exceed their respective limits, their joint probability at this time is expressed as:

$$P(X>x,Y>y)=1-P(X\le x)-P(Y\le y)+P(X\le x,Y\le y)=1-u-v+C(u,v) \quad (3)$$

There are many kinds of copula functions. The Archimedean copula function is widely used in practice because of its simple construction method and good simulation effect (Liu et al., 2015; Wang et al., 2017). The most common Archimedean copula functions are Gaussian copula, Clayton copula and Frank copula. Their function forms are:

$$C^{Gu}(u,v;\alpha)=\exp\left\{-\left[(-Inu)^{\alpha}+(-Inv)^{\alpha}\right]^{\frac{1}{\alpha}}\right\},\alpha>1 \quad (4)$$

$$C^{Cl}(u,v;\alpha)=\left(u^{-\alpha}+v^{-\alpha}-1\right)^{-\frac{1}{\alpha}},\alpha>0 \quad (5)$$

$$C^{Fr}(u,v;\alpha)=-\frac{1}{\alpha}In\left[1+\frac{\left(e^{-\alpha u}-1\right)\left(e^{-\alpha v}-1\right)}{e^{-\alpha}-1}\right],\ \alpha\in(-\infty,0)\cup(0,-\infty) \quad (6)$$

where α is a parameter describing the relationship between variables.

As the marginal distribution is estimated using kernel density method (Cranmer, 2001; Yang et al., 2019), there is no need to estimate the parameters in the marginal distribution. In this paper, the semi-parametric estimation method was used to estimate the parameters (α) of the copula function. The formula is as follows:

$$\hat{\alpha}=\arg\max\sum_{i=1}^{n}In\left[c(u_i,v_i;\alpha)\right] \quad (7)$$

where n is the number of samples, α is the unknown parameter in the copula function, and $c(u_i, v_i; \alpha)$ is a copula density function.

Finally, this work calculated the Euclidean distance (d) between the theoretical copula value and the empirical copula value, which could reflect the fitting of the binary copula function to the original data, thus evaluating the fitting effect of different copula functions. The formula of Euclidean distance is as follows:

$$d=\sum_{i=1}^{n}\left|\hat{C}(F_n(x_i),G_n(y_i))-C(u,v)\right|^2 \quad (8)$$

where $F_n(x)$ and $G_n(y)$ are the empirical distribution functions of samples X and Y, respectively, $\hat{C}(u,v)$ is the empirical copula of samples, $\hat{C}(u,v)=(1/n)\times\sum_{i=1}^{n}I_{[F_n(x_i)\le u]}I_{[G_n(y_i)\le v]}$ and $I_{[\cdot]}$ is the characteristic function. When $F_n(x)\le u$, $I=1$; otherwise $I=0$.

3. Results

3.1. Water Environment Modeling

3.1.1. Calibration of the Model

The hydrodynamic parameters were verified by the monthly measured water depth data in the center of Hanfeng Lake in 2021 (Figure 2). The water quality parameters were verified by the monthly measured water quality data in the HF2 and PX6 sections (Figure 3). The relative error (*RE*) and Nash efficiency coefficient (*NE*) were used to verify the model. The model was confirmed to be stable and reliable when the relative error was less than 20% and the Nash efficiency coefficient was more than 80%. The water depth process and water quality process simulated by the model was in good agreement with the measured value, which demonstrated that the water environment model adequately reflected the changing water quality dynamics of the Pengxi River.

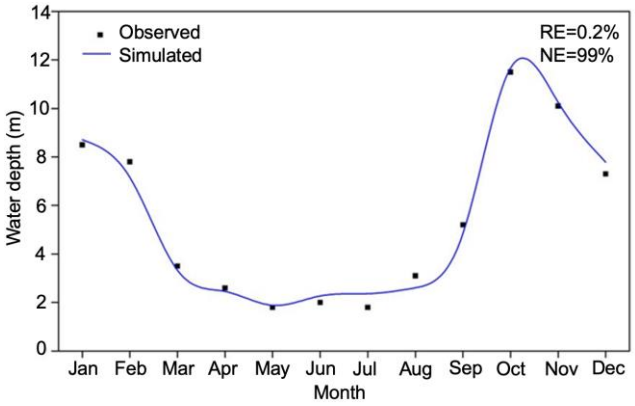

Figure 2. Comparison of the simulated and measured water depths in the middle of Hanfeng Lake.

3.1.2. Hydrodynamic Characteristics

The overall velocity of Hanfeng Lake was low, with an average velocity of 0.023 m/s, and the velocity of the Hanfeng Lake area showed the order of the reservoir tail > reservoir center > dam front (Figure 4). The velocity was higher from June to October, with an average velocity of 0.042 m/s, and the velocity was lower from November to May, with an average velocity of 0.01 m/s. The velocity of PX5 in the main stream of Pengxi River was the highest, and that of PX6 was slightly lower due to the discharge under the regulating dam. Affected by the impoundment of the Three Gorges, the reach above Gaoyang (PX4) showed typical river characteristics in the flood season, and the flow velocity changed greatly. Gaoyang and its lower reaches are permanent backflow areas of Three Gorges Reservoir, and the average velocity along the section was at a low level, less than 0.1 m/s, even reaching the millimeter level.

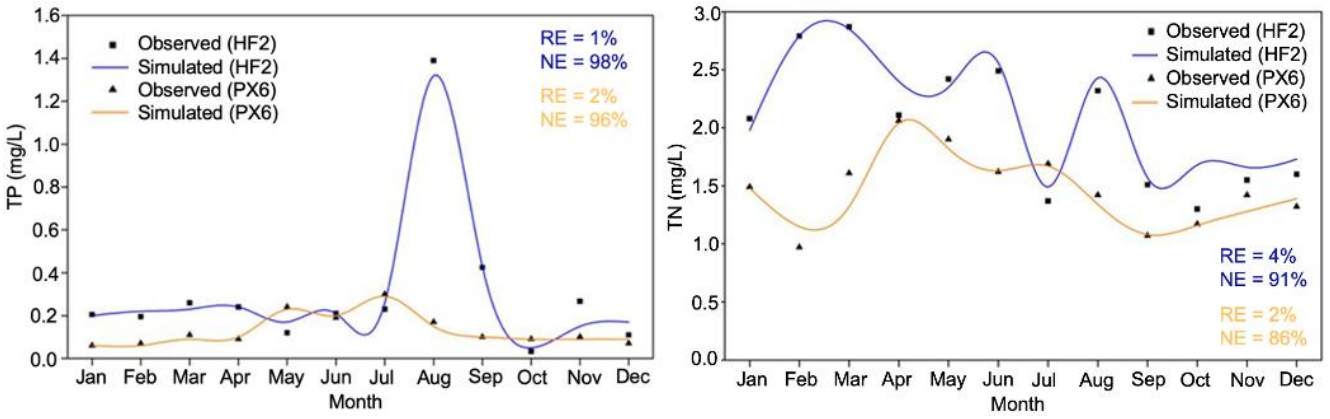

Figure 3. Comparison between the simulated and measured water quality values at the HF2 and PX6 points.

The flow velocity at the estuary increased slightly due to the fluctuation of the Three Gorges water level, showing typical characteristics of reservoirs. The overall flow mobility of the Pengxi River was very poor, which is conducive to the deposition and enrichment of pollutants. In the long run, it is possible to form a eutrophic reservoir area similar to a eutrophic lake, which mainly releases endogenous pollutants.

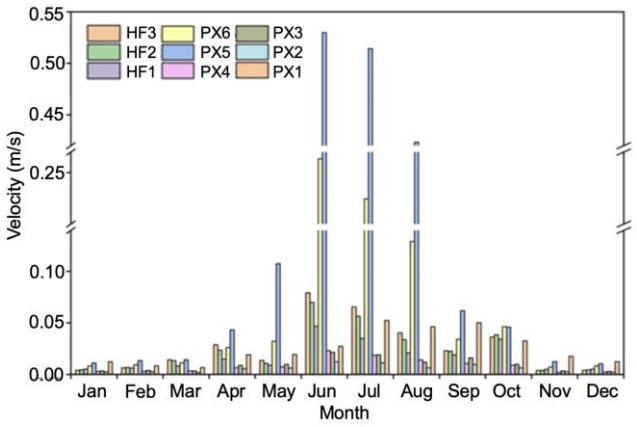

Figure 4. Diurnal variation of the flow velocity in Hanfeng Lake and the main stream of the Pengxi River.

The change process of the daily flow direction in the Hanfeng Lake area and the main stream of the Pengxi River is shown in Figure 5. The flow field in the Hanfeng Lake area was mainly affected by the gravity of the water flow and flowed from west to east. Most of the backflow of Hanfeng Lake occurred in January, and the backflow occurred seven times, each lasting one day. After the implementation of new regulations in September 2021, the Three Gorges impounded water for the first time, and the backflow was advanced from the previous October to September. The backflow occurred three times, each lasting 1 ~ 2 days. The velocity before the backflow was between 0.002 and 0.030 m/s, with an average value of 0.010 m/s, and the velocity during backflow was between 0.002 and 0.023 m/s, with an average value of 0.013 m/s. Relative to the normal situation, the flow pattern in the Hanfeng lake area changed slightly and the velocity increased slightly; however, overall, the velocity was low and could largely be ignored. The reach above Gaoyang (PX4) in the main stream of the Pengxi River exhibited typical river characteristics, and the flow direction was basically one-way except for backflow in part of the water storage period. However, the following reach of Gaoyang was greatly affected by the change in the water level of the main stream, the water flow often reversed, and the backflow lasted for a long time. In particular, at the mouth of the Pengxi River, the flow was greatly affected by the fluctuation of the water level of the Yangtze River and was in a reflux state in the rising and falling periods of the water level.

During the backflow period, part of the water in the main stream of the Pengxi River entered the Puli River and the other part entered Hanfeng Lake (Figure 6). The coordinate system shown in Figure 6 is the projection coordinate, and the units of the *X* and *Y* axes are meters. Compared with the western terrain, the northern terrain of Hanfeng Lake is higher, the water of the Toudao River directly enters the Nan River, and a small amount of water entered the Dong River during the backflow period that only entered the upper reaches of the Dong River estuary. Most of the backflow flowed into the Nan River, and its velocity could be traced to the point where the Taoxi River flows into the Nan River estuary, which has a wide influence range. Due to the backflow congestion, some of the water from the Nanhe River entered the Taoxi River.

3.1.3. Water Quality Characteristics

The temporal and spatial changes of TP in the Pengxi River are shown in Figure 7. The TP concentration in the upper reaches of the Pengxi River was notably higher than that in the lower reaches, while the TP concentration in the main stream of the Yangtze River was the lowest. The annual average TP in Hanfeng Lake was 0.27 mg/L, and the water quality was inferior to the standard of Lake Class V (Chinese Water Standard, 0.2 mg/L). There was a difference in the year: the water quality in August was the worst, followed by that in June, and the water quality in October met the Class III (Chinese Water Standard, 0.05 mg/L) water quality standard of lakes; the difference in other months was not significant. The results showed that the

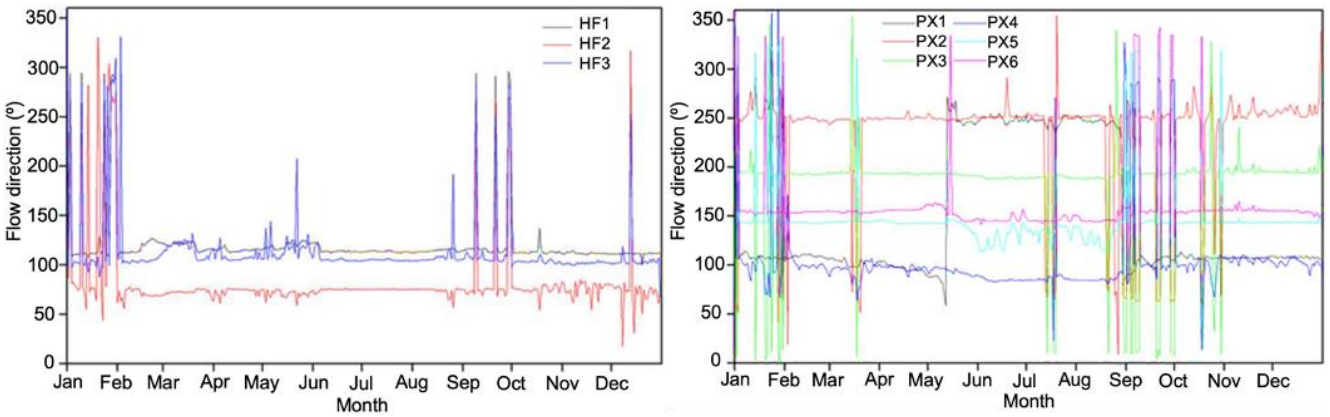

Figure 5. Diurnal variation of the flow direction in Hanfeng Lake and the main stream of the Pengxi River.

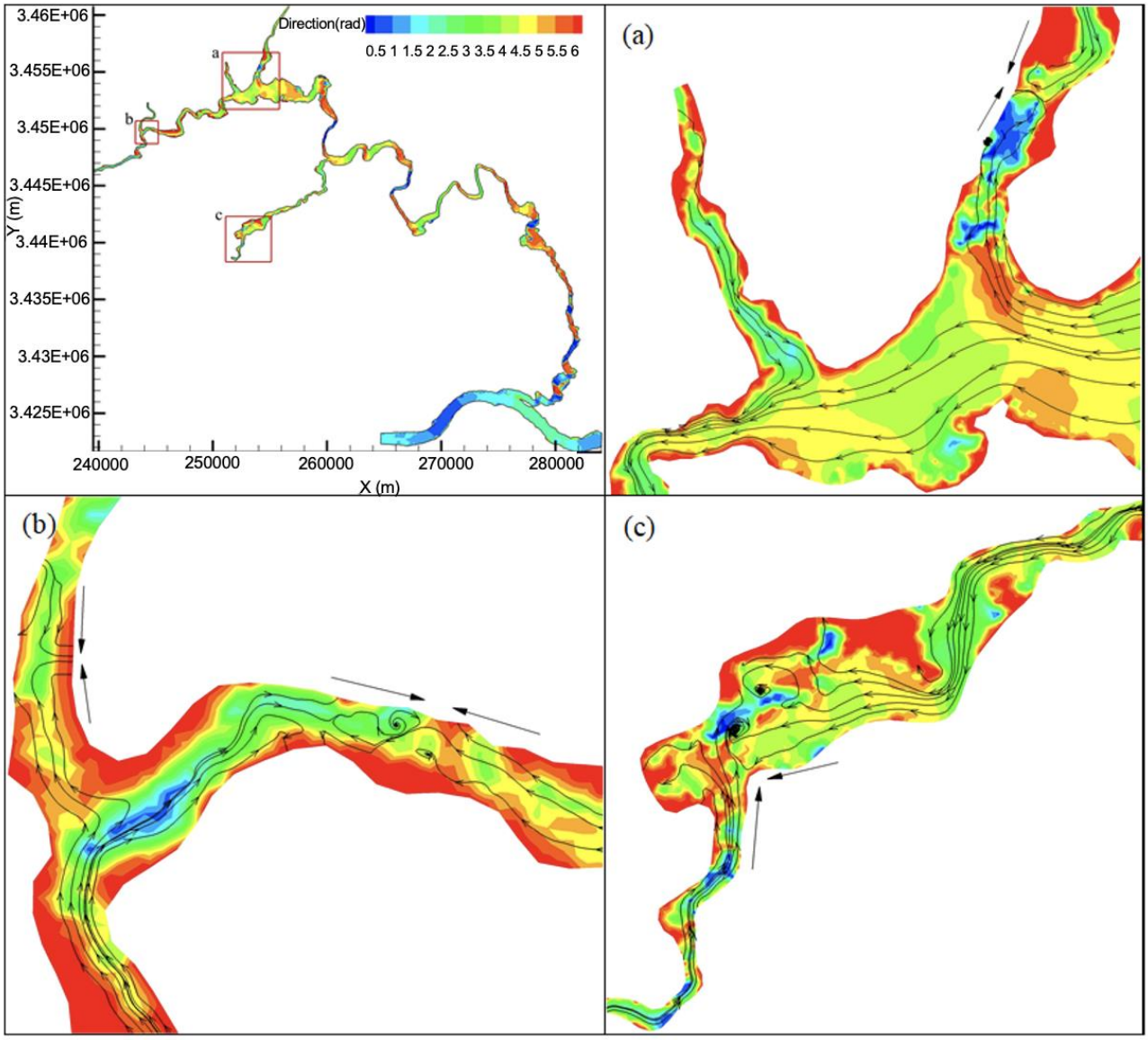

Figure 6. Flow field distribution of Hanfeng Lake in the backflow period.

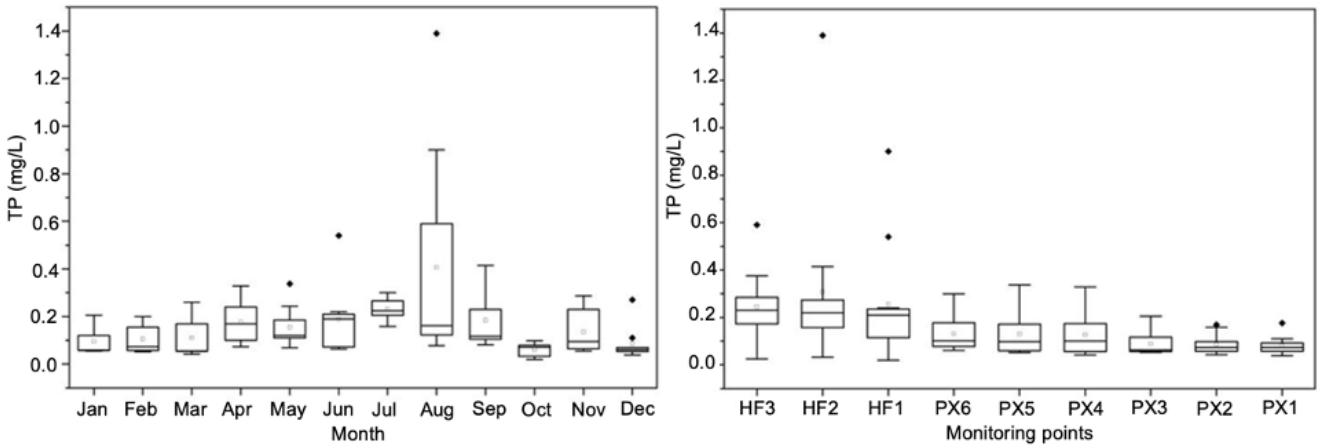

Figure 7. Temporal variation of TP in the Pengxi River.

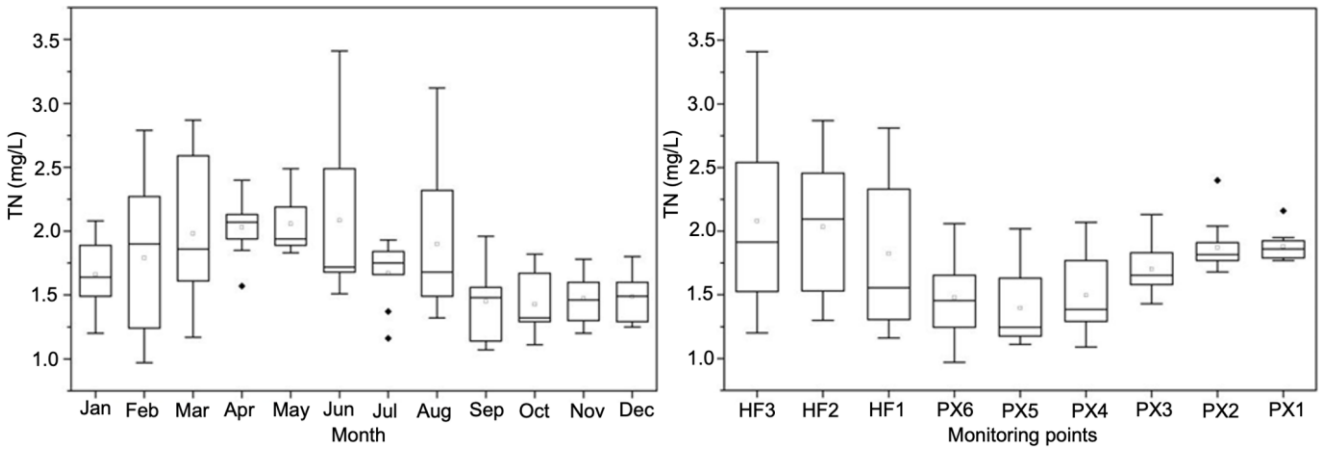

Figure 8. Temporal variation of TN in the Pengxi River.

poor TP water quality in the wet season was mainly due to non-point source pollution. The average concentrations of TP before and after the backflow in Hanfeng Lake were 0.28 and 0.27 mg/L, respectively. The backflow slightly decreased the TP concentration in Hanfeng Lake, which had little effect on Hanfeng Lake.

The TP concentration in the main stream of the Pengxi River was slightly lower than that in Hanfeng Lake, with an annual average concentration of 0.107 mg/L. The PX1-PX4 reach is in the form of a lake year-round, and only some points in March and December met the Class III water quality standard of the lake. The reaches of PX5 and PX6 are lakes from October to March and did not meet the Class III water quality standard of lakes. From April to September, the main stream of the Pengxi River is in a river form, and except for the poor water quality in May and July, and the rest of the months met the Class III (Chinese Water Standard, 0.2 mg/L) water quality standard of rivers. The main stream of the Pengxi River is mainly affected by pollutants from upstream runoff in the wet season, and the TP concentration was high. In the dry season, fewer pollutants are imported from the upstream region, and the dilution of the backwater of the Yangtze River led to a decrease in the TP concentration in the dry season.

The temporal and spatial changes in TN in the Pengxi River are shown in Figure 8. The TN concentration in the Pengxi River was the highest in the upper reaches, followed by the lower and middle reaches. The TN concentration in the Nanhe River and the Taoxi River, tributaries of Hanfeng Lake, was high, resulting in poor water quality in the upper reaches. The lower reaches of the Pengxi River were mainly affected by the backflow of the Three Gorges Reservoir; the concentration of TN in the main stream of the Yangtze River was high, and the backflow caused the concentration in the lower reaches of the Pengxi River to rise. The average TN concentration of Hanfeng Lake was 2.06 mg/L, which was worse than the water quality standard of Class V (Chinese Water Standard, 2 mg/L). The TN in Hanfeng Lake also showed differences during the year, with the highest concentration in May, followed by that in August, and the difference was not significant in other months. The results also showed that the TN concentration was high in the wet season, and the water quality of Hanfeng Lake was mainly affected by non-point source pollution. The average concentrations of TN before and after the backflow in Hanfeng Lake were 1.66 and 1.64 mg/L, respectively. The backflow decreased the TN concentration in Hanfeng Lake. The annual average TN concentration of the main stream of Pengxi River was 1.63 mg/L,

which is the water quality of Class V. The concentration of TN in the PX5 and PX6 reaches of the Pengxi River was high in the wet season, which is greatly affected by non-point source pollution, and lower in the dry season. The PX1-PX4 reach is affected by the backflow of the Three Gorges Reservoir, and TN was always at a stable and high concentration.

3.2. Eutrophication Risk Analysis

3.2.1. Marginal Probability Distribution and Joint Probability Distribution

Through the established water eutrophication model, the sequences of TP and TN were simulated, and the empirical frequency distribution of the simulated sequences of the water eutrophication indicators was obtained. The KS density function in MATLAB was used to estimate the kernel density, which could directly fit the marginal probability distribution according to the simulation data without estimating the parameters in the marginal distribution. The results of dependency measurement showed that the correlation between the TP and TN concentrations was close and positive (Hanfeng Lake: Kendall's τ = 0.90, Spearman's ρ = 0.98; Pengxi River: Kendall's τ = 0.52, Spearman's ρ = 0.63), and the copula function could be used to construct the joint probability distribution of TP and TN. The fitting of the empirical frequency distribution and kernel distribution of TP and TN is shown in Figure 9, respectively. As shown in the figure, the shapes of the kernel distribution estimation curve and the empirical distribution function curve were roughly the same, and the fitting effect was good.

Based on the Gaussian copula, Clayton copula, and Frank copula functions, the joint distribution model of TP and TN was constructed. The parameters of three copula functions were estimated using the semi-parametric estimation method, and the Euclidean distance (d) of the theoretical distribution and empirical distribution of the three copula functions was calculated. The Euclidean distances (d) of the theoretical distribution and empirical distribution of the three copula functions in Hanfeng Lake are 0.1971, 0.8012, and 0.091, respectively. and the Euclidean distances (d) of the three copula functions in the main stream of the Pengxi River are 0.0553, 0.0451, and 0.0537, respectively. The copula function with the smallest Euclidean distance (d) was selected as the joint distribution function, so the Frank copula function and Clayton copula function were selected for Hanfeng Lake and the main stream of the Pengxi River, respectively, to establish joint distribution models. The joint distribution functions of Hanfeng Lake and the main stream of the Pengxi River are shown in Figure 10.

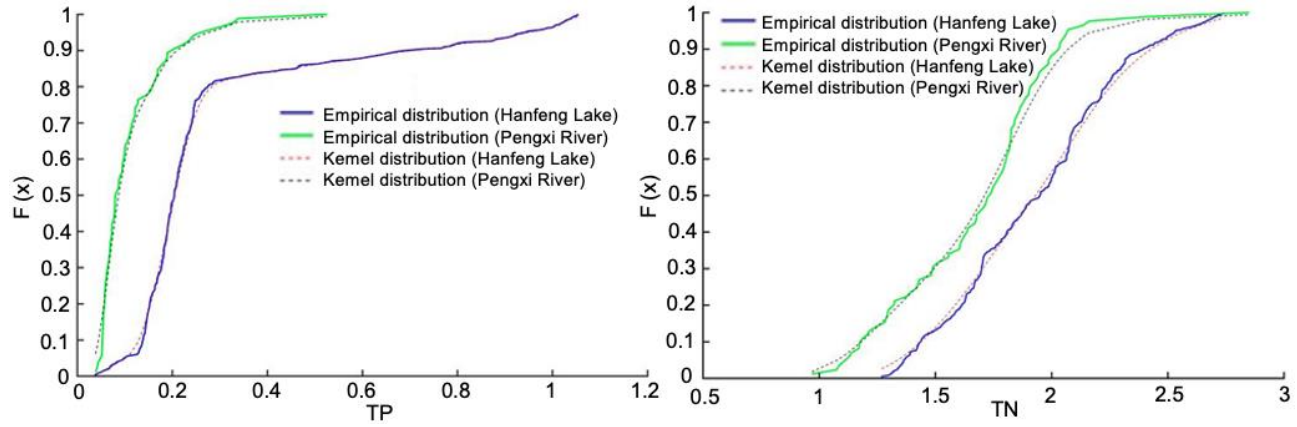

Figure 9. The fitting results of the empirical frequency and calculated frequency of Hanfeng Lake and Pengxi River.

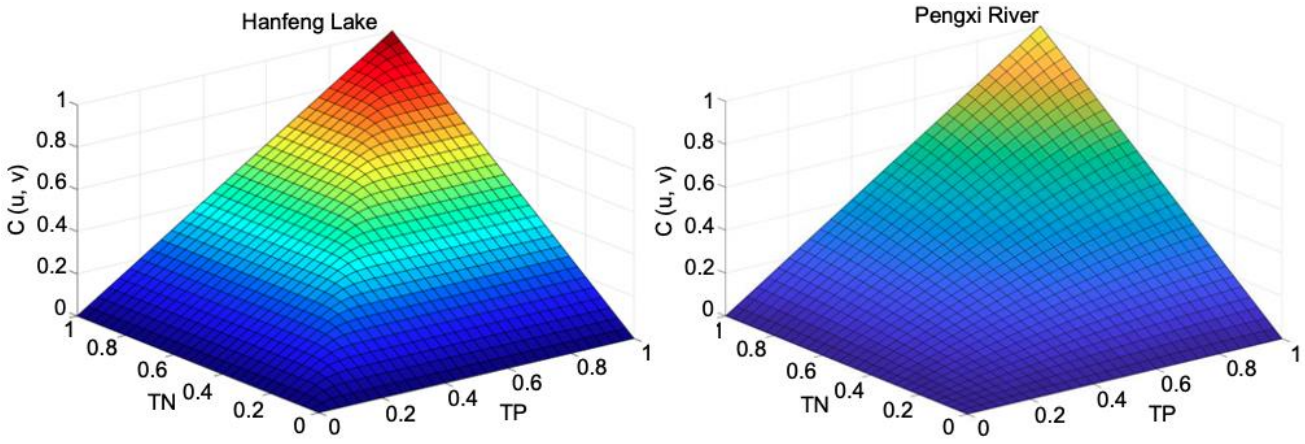

Figure 10. Joint probability distribution of the two-dimensional copula functions of TP and TN.

Table 2. Water Quantity (10^4 m^3) and the TN (t) and TP (t) Fluxes of the Yangtze River Flowing Back into the Pengxi River and Hanfeng Lake

Month	Pengxi River						Hanfeng Lake					
	Past scenario			Present scenario			Past scenario			Present scenario		
	Water quantity	TN	TP	Water quantity	TN	TP	Water quantity	TN	TP	Water quantity	TN	TP
1	935	18	0.5	2,088	40	1.2	253	4	0.2	201	3	0.1
2	563	11	0.4	122	2	0.1	0	0	0.0	0	0	0.0
3	2,687	50	1.5	267	5	0.2	0	0	0.0	0	0	0.0
4	0	0	0.0	0	0	0.0	0	0	0.0	0	0	0.0
5	0	0	0.0	0	0	0.0	0	0	0.0	0	0	0.0
6	0	0	0.0	0	0	0.0	0	0	0.0	0	0	0.0
7	0	0	0.0	4,729	87	8.3	0	0	0.0	0	0	0.0
8	0	0	0.0	4,387	77	3.4	0	0	0.0	0	0	0.0
9	18,486	360	20.4	33,534	652	37.0	0	0	0.0	796	9	0.8
10	12,946	236	12.7	3,670	67	3.6	240	3	0.2	0	0	0.0
11	3,094	55	1.7	1,154	21	0.7	82	1	0.1	0	0	0.0
12	516	9	0.2	199	4	0.1	13	0	0.0	0	0	0.0
Total	39,226	738	37.4	50,150	955	54.5	588	8	0.5	996	12	1.0

According to the joint probability distribution of the TP and TN concentrations in 2021 (Figure 10), when the TP concentration was constant, the joint probability value increased with an increase in the TN concentration. When the TN concentration remained unchanged, the joint probability value increased with an increase in the TP concentration. There was a positive correlation between the TP and TN concentrations; that is, the change trends of TP and TN were similar. This may have been due to the developed economy and a large amount of pollution discharge in the basin. In addition, the periodic fluctuation in the water level in the Three Gorges Reservoir aggravates soil erosion, leading to nutrient loss and water quality deterioration (Wang et al., 2016). Previous studies of the Pengxi River have shown that an exogenous nutrient input intensified the proliferation of dominant algae in the Pengxi River (Shi et al., 2017). Ouyang et al. (2021) discovered that TP significantly affected the cyanobacteria community, while TN significantly affected the phytoplankton community. These conclusions are consistent with the current results. Therefore, the eutrophication risk of Pengxi River requires attention.

3.2.2. Influence of Reflux on the Eutrophication Risk

To study the influence of backwater on the eutrophication of tributaries in the reservoir area and keep the inlet boundary condition unchanged that is, only changing the outlet water level boundary condition we analyzed the eutrophication risk of the Pengxi River under different water level operation conditions. Two different water level scenarios (the past scenario, corresponding to the experimental impoundment period, and the present scenario, corresponding to the normal operation period) were assumed, and the fluxes of TN and TP flowing back into the Pengxi River were counted under the two scenarios (Table 2). The amount of water and pollution flowing back into Hanfeng Lake and Pengxi River in the present scenario was greater than that in the past scenario. Most of the pollutants from the Yangtze River flowing back remained in the main stream of the Pengxi River, while a small amount entered the tributaries. The main stream of the Pengxi River was greatly affected by the fluctuation of the Three Gorges water level, and pollutants from the Yangtze River flowed back into it in most months. Hanfeng Lake is affected by backflow during the high water level operation of the Three Gorges. The largest months of pollutant input were September and October, when the Three Gorges began to store water and entered the rising water level period. It can be seen that during the suitable growth period of algae (September ~ November) (Su et al., 2022; Yang et al., 2022), the quantity of TN and TP in the tributaries was readily affected by the backflow of the main stream, which may affect algal bloom outbreaks in the tributaries.

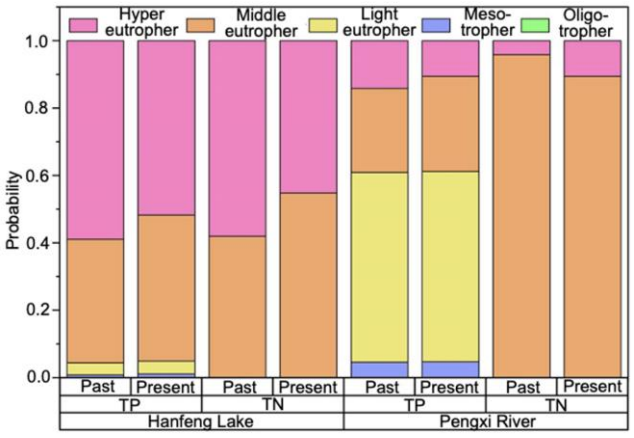

Figure 11. Probability of the different nutrient levels of TP and TN.

Figure 11 shows the probability that the TP and TN in Hanfeng Lake and the Pengxi River were at different levels under different scenarios. The TN in Hanfeng Lake and the main stream of the Pengxi River was always above the level of moderate eutrophication, while the TP varied over a wide range, from mesotrophic to hyper-eutrophic. It can be seen that the TN was less affected by external factors, and its concentration was always at a high level. The eutrophication level of the Pengxi River Basin was largely determined by TP, and the primary goal of pol-

lution control is to control the TP. Both the TP and TN in Hanfeng Lake accounted for the largest proportion of hype-reutrophic events, and an increase in backwater would cause the TP and TN concentrations in Hanfeng Lake to decrease more than that in the past. The probability of TP being at a hyper-eutrophic level decreased from 59 to 52%, and the probability of TN being at a hypereutrophic level decreased from 58 to 45%. The slight eutrophic level of TP and moderately eutrophic level of TN accounted for the largest proportion in the Pengxi River. Compared with the past scenario, the TP concentration in Pengxi River in the present scenario was lower than that in the past scenario, but the TN concentration was higher; the probability of TP being at a hyper-eutrophic level decreased from 14 to 11%, while the probability of TN being at a hyper-eutrophic level increased from 4 to 10%.

Table 3 shows the joint risk of the TP and TN concentrations. In Hanfeng Lake, the joint risk probability of TP and TN was the highest when they were both hyper-eutrophic, followed by TP and TN being both moderately eutrophic. With an increase in backwater under the present scenario, the probability that both TP and TN were hyper-eutrophic ranged from 56 to 45%, and the probability that both TP and TN were moderately eutrophic increased from 37 to 43%. The joint probability of the other nutrient levels increased slightly. Most of the pollution in the Pengxi River basin is distributed in the range of Hanfeng Lake, and a large amount of pollution discharge leads to a high water quality concentration in Hanfeng Lake. During the water storage period (September ~ October), a considerable amount of backwater from the main stream of the Yangtze River is refluxed into Pengxi River, resulting in an increase in the water level, which pushes the low-concentration main stream water body into the waters of Hanfeng Lake. During the high water level period (November ~ January), the water level of the main stream is stable and greater than 170 m (when the water level is above 168.5 m, Hanfeng Lake is connected with the Pengxi River), which leads to the continuous exchange of backflow water with the water of Hanfeng Lake, thus diluting the lake's water.

In the main stream of the Pengxi River, when TP is slightly eutrophic and TN is moderately eutrophic, the joint risk probability is the highest, and the backwater of the Yangtze River reduces the risk probability from 52 to 42%. In the main stream of the Pengxi River, when TP is slightly eutrophic and TN is moderately eutrophic, the joint risk probability of TP and TN is the highest, and the risk probability decreases from 52 to 42% due to an increase in the backwater under the present scenario. When TN is in severe eutrophication, the joint risk probability of TP with different nutritional levels increases. The pollution discharge of the Pengxi River is small, but the TP concentration is still higher than that of the Yangtze River due to the influence of its upstream reaches, and the TN concentration is slightly lower than that of the Yangtze River. The frequent exchange between the Pengxi River and the Yangtze River causes the TP concentration in the Pengxi River to decrease and the TN concentration to increase. Therefore, the TP concentration in the main stream of the Pengxi River gradually decreases from upstream to downstream, while TN gradually increases from upstream to downstream.

Table 3. Two-Dimensional Joint Risk Probability of TP and TN

Joint risk (Hanfeng Lake)			TP (%)			
			Mesotrophic	Slightly eutrophic	Moderately eutrophic	Hyper-eutrophic
Past scenario	TN	Moderately eutrophic	0.82	3.56	36.71	2.08
		Hyper-eutrophic	0.00	0.00	1.26	55.58
Present scenario	TN	Moderately eutrophic	1.10	3.84	43.29	6.72
		Hyper-eutrophic	0.00	0.00	0.14	45.07
Joint risk (Pengxi River)			TP (%)			
			Mesotrophic	Slightly eutrophic	Moderately eutrophic	Hyper-eutrophic
Past scenario	TN	Moderately eutrophic	4.52	52.08	24.00	12.05
		Hyper-eutrophic	0.05	1.11	2.05	4.15
Present scenario	TN	Moderately eutrophic	4.52	42.13	24.74	7.12
		Hyper-eutrophic	0.18	3.63	7.12	10.59

4. Discussion

The impoundment of the Three Gorges Reservoir has led to the deterioration of the water environment in the reservoir area; therefore, evaluating the eutrophication risk in the Three Gorges Reservoir is of great significance (Zhang et al., 2020; Chen et al., 2021; Cheng et al., 2021). In this study, based on the simulation results of the water quality model, we used the copula function to analyze the joint risk probability of eutrophication under different index combinations. We then predicted the probability of eutrophication under different combinations by adjusting the environmental factors that affect water eutrophication. Correlation analysis showed that TP was closely related to the TN index, and using the copula function to construct the joint probability distribution model was suitable. The joint probability distribution established in this study could better quantify the eutrophication risk of the Pengxi River.

The results showed that there was a positive correlation between the TP and TN concentrations, and that the increasing and decreasing trends of TP and TN were basically the same due to the influence of external pollution. The TN in Hanfeng Lake and the main stream of the Pengxi River was always above the level of moderate eutrophication, while the TP varied over a large range, from mesotrophic to hyper-eutrophic. The joint risk probability of TP and TN was the highest when they were both hyper-eutrophic in Hanfeng Lake, and the joint risk probability was the highest when TP was slightly eutrophic and TN was moderately eutrophic in Pengxi River. The results of

this study were consistent with those of previous studies, which found that the eutrophication of the Three Gorges reservoir area was serious after impoundment and that TP was the limiting factor for eutrophication in the Three Gorges Reservoir (Sha et al., 2015; Zhang et al., 2016; Xu et al., 2022).

The influence of the Three Gorges Reservoir backwater on the water quality of tributaries primarily depends on the background concentration of the tributaries. Our results showed that the backwater of the Yangtze River reduced the eutrophication risk of the Pengxi River, which was inconsistent with other tributaries in the reservoir area. Yang et al. (2018) found that the backflow of the Yangtze River brought a large amount of nutrients into the Xiangxi River, which led to eutrophication. Zhao et al. (2016) found that the backflow of high concentration water from the Yangtze River led to an increase in the water quality concentration in Daning River. The primary reason for this difference was that the utilization rate of urban land in the Xiangxi River and Daning River was small, the loads of point sources and non-point sources were low, and the output risk probability was small (Shen et al., 2008). The water quality of the main stream of the Yangtze River was higher than that of the Xiangxi River and Daning River. Although the backwater of the main stream of the Yangtze River reduced the eutrophication risk of Pengxi River, the impact was not great, and the eutrophication of the Pengxi River cannot be ignored.

Compared with previous studies, this study considered the joint risk probability of different indicators, which provided a scientific basis for the prevention and control of eutrophication in the Three Gorges Reservoir (Jimeno-Saez et al., 2020). Copula functions can not only be used to construct the joint probability distribution of two indicators, but can also be used to construct the joint probability distribution of three eutrophication indicators (Tahroudi et al., 2020). One limitation of our study was that only the Archimedean copula function was considered to construct the joint distribution model, and the Archimedean copula function was not necessarily the best fitting function. In the future, more types of copula functions should be considered to construct the joint probability distribution of three-dimensional eutrophication indicators.

5. Conclusions

This study quantified the eutrophication risk of typical tributaries in the Three Gorges Reservoir from a new perspective considering the joint effect of TP and TN concentrations. The corresponding joint probability distribution was introduced using the copula theory. The optimal copula models used for Hanfeng Lake and Pengxi River were the Frank copula and Clayton copula, respectively. Then, this study quantified the eutrophication risk of the Pengxi River and demonstrated the joint risk probability of TP and TN with different nutritional levels. The findings also indicated that the water from the main stream flowing back into the tributaries due to the impoundment of the Three Gorges Reservoir would reduce the eutrophication risk of the Pengxi River. These findings can provide scientific support for the eutrophication control of the Three Gorges Reservoir.

This study only considers the joint eutrophication risk of TP and TN indicators, although Chl-a is also an important indicator used to reflect the eutrophication level. Future research can consider the joint eutrophication risk of three water quality factors (such as TP, TN, and Chla). Moreover, more potential copula functions can be involved to optimize the joint probability distribution model of multiple variables. The comprehensive evaluation of the joint effect of multiple variables can better reveal the eutrophication risk in the reservoir area.

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References

AghaKouchak, A., Chiang, F., Huning, L.S., Love, C.A., Mallakpour, I., Mazdiyasni, O., Moftakhari, H., Papalexiou, S.M., Ragno, E. and Sadegh, M. (2020). Climate extremes and compound hazards in a warming world. *Annu. Rev. Earth Planet. Sci.*, 48, 519-548. https://doi.org/10.1146/annurev-earth-071719-055228

Ahn, J., Na, Y. and Park, S.W. (2019). Development of two-dimensional inundation modelling process using MIKE21 model. *KSCE J. Civ. Eng.*, 23, 3968-3977. https://doi.org/10.1007/s12205-019-1586-9

Chen, Z.M., Shi, M.Q. and Zou, J.S. (2021). Application of improved fuzzy comprehensive evaluation method in eutrophication assessment for tributary bays in the Three Gorges Reservoir, China. *Water Environ. Res*., 93(6), 808-816. https://doi.org/10.1002/wer.1465

Cheng, Q., Long, Z. and Li, Z. (2021). Research on the interaction of environmental factors in the Three Gorges Reservoir area based on the two-layer network system dynamics model. *IOP Conf. Ser.: Earth Environ. Sci.*, 693, 012076. https://doi.org/10.1088/1755-1315/693/1/012076

Conrad, S.R., Santos, I.R., White, S. and Sanders, C.J. (2019). Nutrient and trace metal fluxes into estuarine sediments linked to historical and expanding agricultural activity (Hearnes Lake, Australia). *Estuaries Coasts*, 42, 944-957. https://doi.org/10.1007/s12237-019-00541-1

Cranmer, K. (2001). Kernel estimation in high-energy physics. *Comput. Phys. Commun.*, 136(3), 198-207. https://doi.org/10.1016/S0010-4655(00)00243-5

Daneshkhah, A., Remesan, R., Chatrabgoun, O. and Holman, P. (2016). Probabilistic modeling of flood characterizations with parametric and minimum information pair-copula model. *J. Hydrol.*, 540, 469-487. https://doi.org/10.1016/j.jhydrol.2016.06.044

Gao, Q., He, G., Fang, H., Bai, S. and Huang, L. (2018). Numerical simulation of water age and its potential effects on the water quality in Xiangxi Bay of Three Gorges Reservoir. *J. Hydrol.*, 566, 484-499. https://doi.org/10.1016/j.jhydrol.2018.09.033

He, Q., Kang, L., Sun, X., Jia, R., Zhang, Y., Ma, J., Li, H. and Ai, H. (2018). Spatiotemporal distribution and potential risk assessment of microcystins in the Yulin River, a tributary of the Three Gorges Reservoir, China. *J. Hazard. Mater.*, 347, 184-195. https://doi.org/10.1016/j.jhazmat.2018.01.001

Huang, Y., Fan, D., Liu, D., Song, L., Ji, D. and Hui, E. (2016). Nutrient estimation by HJ-1 satellite imagery of Xiangxi Bay, Three Gorges Reservoir, China. *Environ. Earth Sci.*, 75, 1-13. https://doi.org/10.1007/s12665-016-5421-z

Ji, D., Wells, S.A., Yang, Z., Liu, D., Huang, Y., Ma, J. and Berger, C. J. (2017). Impacts of water level rise on algal bloom prevention in the tributary of Three Gorges Reservoir, China. *Ecol. Eng.*, 98, 70-81. https://doi.org/10.1016/j.ecoleng.2016.10.019

Jia, P., Wang, Q., Lu, X., Zhang, B., Li, C., Li, S., Li, S. and Wang, Y. (2018). Simulation of the effect of an oil refining project on the water environment using the MIKE 21 model. *Phys. Chem. Earth*, 103,

91-100. https://doi.org/10.1016/j.pce.2017.02.003

Jimeno-Sáez, P., Senent-Aparicio, J., Cecilia, J. and Pérez-Sánchez, J. (2020). Using machine-learning algorithms for eutrophication modeling: case study of Mar Menor Lagoon (Spain). *Int. J. Environ. Res. Public Health*, 17(4), 1189-1203. https://doi.org/10.3390/ijerph17041189

Johnson, G.E. and Rainey, W.S. (2012). Eco-design of river fishways for upstream passage: application for Hanfeng Dam, Pengxi River, China. *J. Chongqing Norm. Univ.*, 29(3), 16-23. https://doi.org/10.11721/cqnuj20120320

Lee, T. (2018). Multisite stochastic simulation of daily precipitation from copula modeling with a gamma marginal distribution. *Theor. Appl. Climatol.*, 132, 1089-1098. https://doi.org/10.1007/s00704-017-2147-0

Li, T., He, B., Zhang, Y., Fu, S., Zhang, Y. and Long, X. (2021). Spatiotemporal dynamics of coupled dissolved silica and bicarbonate in a dam-induced urban lake system in the Three Gorges Reservoir area. *J. Hydrol.*, 597, 126181. https://doi.org/10.1016/j.jhydrol.2021.126181

Lian, J., Yao, Y., Ma, C. and Guo, Q. (2014). Reservoir operation rules for controlling algal blooms in a tributary to the impoundment of Three Gorges Dam. *Water*, 6(10), 3200-3223. https://doi.org/10.3390/w6103200

Liao, Y.J., Zhao, H.T., Jiang, Y., Ma, Y.K., Luo, X. and Li, X.Y. (2019). An innovative method based on cloud model learning to identify high-risk pollution intervals of storm-flow on an urban catchment scale. *Water Res.*, 165, 115007. https://doi.org/10.1016/j.watres.2019.115007

Lin, S.S., Shen, S.L., Zhou, A. and Lyu, H.M. (2021). Assessment and management of lake eutrophication: A case study in Lake Erhai, China. *Sci. Total Environ.*, 751, 141618. https://doi.org/10.1016/j.scitotenv.2020.141618

Liu, D., Yang, Z., Ji, D., Ma, J., Cui, Y. and Song, L. (2016). A review on the mechanism and its controlling methods of the algal blooms in the tributaries of Three Gorges Reservoir. *J. Hydraul. Eng.*, 47(3), 443-454. https://doi.org/10.13243/j.cnki.slxb.20151304

Liu, L., Liu, D., Johnson, D.M., Yi, Z. and Huang, Y. (2012). Effects of vertical mixing on phytoplankton blooms in Xiangxi Bay of Three Gorges Reservoir: implications for management. *Water Res.*, 46(7), 2121-2130. https://doi.org/10.1016/j.watres.2012.01.029

Liu, X., Li, N., Yuan, S., Xu, N., Shi, W. and Chen, W. (2015). The joint return period analysis of natural disasters based on monitoring and statistical modeling of multidimensional hazard factors. *Sci. Total Environ.*, 538, 724-732. https://doi.org/10.1016/j.scitotenv.2015.08.093

Long, L.H., Ji, D.B., Yang, Z.Y., Cheng, H.Q., Yang, Z.J., Liu, D.F., Liu, L. and Lorke, A. (2020). Tributary oscillations generated by diurnal discharge regulation in Three Gorges Reservoir. *Environ. Res. Lett.*, 15, 084011. https://doi.org/10.1088/1748-9326/ab8d80

Ouyang, W., Li, Z., Yang, J., Lu, L. and Guo, J. (2021). Spatio-temporal variations in Phytoplankton communities in sediment and surface water as reservoir drawdown – A case study of Pengxi River in Three Gorges Reservoir, China. *Water*, 13(3), 340-355. https://doi.org/10.3390/w13030340

Pernet-Coudrier, B., Qi, W., Liu, H., Müller, B. and Berg, M. (2012). Sources and pathways of nutrients in the semi-arid region of Beijing – Tianjin, China. *Environ. Sci. Technol.*, 46(10), 5294-5301. https://doi.org/10.1021/es3004415

Ran, X., Bouwman, A.F., Yu, Z. and Liu, J. (2019). Implications of eutrophication for biogeochemical processes in the Three Gorges Reservoir, China. *Reg. Environ. Change*, 19, 55-63. https://doi.org/10.1007/s10113-018-1382-y

Ran, X., Yu, Z., Yao, Q., Chen, H. and Mi, T. (2010). Major ion geochemistry and nutrient behaviour in the mixing zone of the Changjiang (Yangtze) River and its tributaries in the Three Gorges Reservoir. *Hydrol. Processes*, 24(17), 2481-2495. https://doi.org/10.1002/hyp.7684

Sadegh, M., Ragno, E. and AghaKouchak, A. (2017). Multivariate Copula Analysis Toolbox (MvCAT): describing dependence and underlying uncertainty using a Bayesian framework. *Water Resour. Res.*, 53(6), 5166-5183. https://doi.org/10.1002/2016WR020242

Schumann, A. (2017). Flood safety versus remaining risks-options and limitations of probabilistic concepts in flood management. *Water Resour. Manage.*, 31, 3131-3145. https://doi.org/10.1007/s11269-017-1700-z

Sha, Y., Wei, Y., Li, W., Fan, J. and Cheng, G. (2015). Artificial tide generation and its effects on the water environment in the backwater of Three Gorges Reservoir. *J. Hydrol.*, 528, 230-237. https://doi.org/10.1016/j.jhydrol.2015.06.020

Shen, Z., Hong, Q., Yu, H. and Liu, R. (2008). Parameter uncertainty analysis of the non-point source pollution in the Daning River watershed of the Three Gorges Reservoir Region, China. *Sci. Total Environ.*, 405(1-3), 195-205. https://doi.org/10.1016/j.scitotenv.2008.06.009

Shi, Y., Xu, G., Wang, Y., Engel, B.A., Peng, H., Zhang, W., Cheng, M. and Dai, M. (2017). Modelling hydrology and water quality processes in the Pengxi River basin of the Three Gorges Reservoir using the soil and water assessment tool. *Agric. Water Manage.*, 182, 24-38. https://doi.org/10.1016/j.agwat.2016.12.007

Strokal, M., Kahil, T., Wada, Y., Albiac, J., Bai, Z., Ermolieva, T., Langan, S., Ma, L., Oenema, O., Wagner, F., Zhu, X. and Kroeze, C. (2020). Cost-effective management of coastal eutrophication: A case study for the Yangtze River Basin. *Resour., Conserv. Recycl.*, 154, 104635. https://doi.org/10.1016/j.resconrec.2019.104635

Su, Y., Hu, M., Wang, Y., Zhang, H., He, C., Wang, Y., Wang, D., Wu, X., Zhang, Y., Hong, S. and Trolle, D. (2022). Identifying key drivers of harmful algal blooms in a tributary of the Three Gorges Reservoir between different seasons: causality based on data-driven methods. *Environ. Pollut.*, 297, 118759. https://doi.org/10.1016/j.envpol.2021.118759

Sun, J., Yuan, X., Liu, H. and Liu, G. (2021). Emergy and eco-exergy evaluation of wetland reconstruction based on ecological engineering approaches in the three Gorges Reservoir, *China. Ecol. Indic.*, 122, 107278. https://doi.org/10.1016/j.ecolind.2020.107278

Sun, R., Yuan, X., Chen, Z., Zhang, Y. and Liu, H. (2010). Patterns of plant community species richness in the fluctuating water level zone along the Pengxihe River of the Three Gorges Reservoir. *Res. Environ. Sci.*, 23(11), 1382-1389. https://doi.org/10.13198/j.res.2010.11.53.sunr.001

Sun, R., Yuan, X., Chen, Z., Zhang, Y. and Liu, H. (2012). Effect of Three Georges Reservoir (Yangzi River) on the plant species richness in drawdown zone downstream the tributary river (Pengxi River). *Russ. J. Ecol.*, 43, 307-314, https://doi.org/10.1134/ S1067413612040121

Tahroudi, M.N., Ramezani, Y., De Michele, C. and Mirabbasi, R. (2020). Analyzing the conditional behavior of rainfall deficiency and groundwater level deficiency signatures by using copula functions. *Hydrol. Res.*, 51(6), 1332-1348. https://doi.org/10.2166/nh.2020.036

Van Meter, K.J., Chowdhury, S., Byrnes, D.K. and Basu, N.B. (2020). Biogeochemical asynchrony: Ecosystem drivers of seasonal concentration regimes across the Great Lakes Basin. *Limnol. Oceanogr.*, 65(4), 848-862. https://doi.org/10.1002/lno.11353

Vinçon-Leite, B. and Casenave, C. (2019). Modelling eutrophication in lake ecosystems: A review. *Sci. Total Environ.*, 651(2), 2985-3001. https://doi.org/10.1016/j.scitotenv.2018.09.320

Wang, L.P., Zheng, B.H., Zhang, J.L., Liu, X. and Wu, G. (2012). Effects on euthrophication and hydrodynamics of Daning River after impoundment of Three Gorges Reservoir. *J. Lake Sci.*, 24(2), 232-237. https://doi.org/10.18307/2012.0210

Wang, L.J., Wu, L., Hou, X.Y., Zheng, B.H., Li, H. and Norra, S. (2016). Role of reservoir construction in regional land use change

in Pengxi River basin upstream of the Three Gorges Reservoir in China. *Environ. Earth Sci.*, 75, 1048-1063. https://doi.org/10.1007/s12665-016-5758-3

Wang, X., Zang, N., Liang, P., Cai, Y., Li, C. and Yang, Z. (2017). Identifying priority management intervals of discharge and TN/TP concentration with copula analysis for Miyun Reservoir inflows, North China. *Sci. Total Environ.*, 609, 1258-1269. https://doi.org/10.1016/j.scitotenv.2017.07.135

Wu, D., Yan, H., Shang, M., Shan, K. and Wang, G. (2017). Water eutrophication evaluation based on semi-supervised classification: A case study in Three Gorges Reservoir. *Ecol. Indic.*, 81, 362-372. https://doi.org/10.1016/j.ecolind.2017.06.004

Xu, T., Ma, W., Cheng, Y., Qi, D., Sun, L. and Chang, F. (2022). How has the eutrophication evolved in the tributary bay of the Three Gorges Reservoir area. *AQUA – Water Infrastruct. Ecosyst. Soc.*, 71 (8), 896-909. https://doi.org/10.2166/aqua.2022.026

Xu, Z., Cai, X., Yin, X., Su, M., Wu, Y. and Yang, Z. (2019). Is water shortage risk decreased at the expense of deteriorating water quality in a large water supply reservoir? *Water Res.*, 165, 114984. https://doi.org/10.1016/j.watres.2019.114984

Yang, Z., Xu, P., Liu, D., Ma, J., Ji, D. and Cui, Y. (2018). Hydrodynamic mechanisms underlying periodic algal blooms in the tributary bay of a subtropical reservoir. *Ecol. Eng.*, 120, 6-13. https://doi:10.1016/j.ecoleng.2018.05.003

Yang, P., Xia, J., Zhang, Y., Zhan, C. and Sun, S. (2019). How is the risk of hydrological drought in the Tarim River Basin, Northwest China? *Sci. Total Environ.*, 693, 133555. https://doi.org/10.1016/j.scitotenv.2019.07.361

Yang, Z., Wei, C., Liu, D., Lin, Q., Huang, Y., Wang, C., Ji, D., Ma, zJ. and Yang, H. (2022). The influence of hydraulic characteristics on algal bloom in three gorges reservoir, China: A combination of cultural experiments and field monitoring. *Water Res.*, 211, 118030. https://doi.org/10.1016/j.watres.2021.118030

Zajac, Z., Revilla-Romero, B., Salamon, P., Burek, P., Hirpa, F.A. and Beck, H. (2017). The impact of lake and reservoir parameterization on global streamflow simulation. *J. Hydrol.*, 548, 552-568. https://doi.org/10.1016/j.jhydrol.2017.03.022.

Zang, N., Zhu, J., Wang, X., Liao, Y., Cao, G., Li, C., Liu, Q. and Yang, Z. (2022). Eutrophication risk assessment considering joint effects of water quality and water quantity for a receiving reservoir in the south-to-north water transfer project, China. *J. Cleaner Prod.*, 331, 129966. https://doi.org/10.1016/j.jclepro.2021.129966

Zeng, Q., Qin, L., Bao, L., Li, Y. and Li, X. (2016). Critical nutrient thresholds needed to control eutrophication and synergistic interactions between phosphorus and different nitrogen sources. *Environ. Sci. Pollut. Res.*, 23, 21008-21019. https://doi.org/ 10.1007/s11356-016-7321-x

Zhang, L., Tian, M., Peng, C., Fu, C., Li, T., Chen, Y., Qiu, Y., Huang, Y., Wang, H., Li, Z. and Yang, F. (2020). Nitrogen wet deposition in the Three Gorges Reservoir area: Characteristics, fluxes, and contributions to the aquatic environment. *Sci. Total Environ.*, 738, 140309. https://doi.org/10.1016/j.scitotenv.2020.140309

Zhang, J.L., Wang, L.J., Zheng, B.H., Liu, D.F. and Yang, Z.J. (2016). Eutrophication status of the Daning River within the Three Gorges Reservoir and its controlling factors before and after experimental impoundment. *Environ. Earth Sci.*, 75, 1182-1193. https://doi.org/10.1007/s12665-016-5931-8

Zhang, Y., Li, M.X., Dong, J.F., Yang, H., Van Zwieten, L., Lu, H., Alshameri, A., Zhan, Z.H., Chen, X., Jiang, X.D., Xu, W.C., Bao, Y.P. and Wang, H.L. (2021). A critical review of methods for analyzing freshwater eutrophication. *Water*, 13(2), 225-245. https://doi.org/10.3390/w13020225

Zhao, Y., Zheng, B., Wang, L., Qin, Y., Li, H. and Cao, W. (2016). Characterization of mixing processes in the confluence zone between the Three Gorges Reservoir mainstream and the Daning River using stable isotope analysis. *Environ. Sci. Technol.*, 50(18), 9907-9914. https://doi.org/10.1021/acs.est.5b01132

Zhou, G., Zhao, X., Bi, Y., Liang, Y., Hu, J., Yang, M., Mei, Y., Zhu, K., Zhang, L. and Hu, Z. (2011). Phytoplankton variation and its relationship with the environment in Xiangxi Bay in spring after damming of the Three-Gorges, China. *Environ. Monit. Assess.*, 176, 125-141. https://doi.org/10.1007/s10661-010-1571-8

Zhu, K.W., Chen, Y.C., Zhang, S., Lei, B., Yang, Z.M. and Huang, L. (2020). Vegetation of the water-level fluctuation zone in the Three Gorges Reservoir at the initial impoundment stage. *Global Ecol. Conserv.*, 21, e00866. https://doi.org/10.1016/j.gecco.2019.e00866