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EDITED BY
Peiyue Li,
Chang'an University, China

REVIEWED BY
Jianhua Wu,
Chang'an University, China
Md Mamun,
Chungnam National University, Republic of Korea

*CORRESPONDENCE
Lin Ye,
yelin@ihb.ac.cn
Qinghua Cai,
qhcai@ihb.ac.cn

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Ecological water quality of the Three Gorges Reservoir and its relationship with land covers in the reservoir area: implications for reservoir management

Lin Ye[1]*, Kefeng Chen[1], Jingjing Cheng[1], Lu Tan[1], Min Zhang[2], Xiaoguang Zhang[1,3] and Qinghua Cai[1]*

[1]State Key Laboratory of Freshwater Ecology and Biotechnology, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan, China, [2]Department of Water Ecology and Environment, China Institute of Water Resources and Hydropower Research, Beijing, China, [3]College of Advanced Agricultural Sciences, University of Chinese Academy of Sciences, Beijing, China

In this study, we evaluated the ecological water quality of the entire Three Gorges Reservoir (TGR) and further examined the relationship with changes in watershed land covers. Using the phytoplankton functional group-based Q index, we found that the ecological water quality in the mainstream (previously known as the Yangtze River) of TGR is good, with 84% of sites in the status above good. While the poor ecological water quality was generally observed in the backwater regions of TGR's tributaries, with 79% of sites below the good status. Further investigating the potential impacts of the changes in land covers within the watershed on the tributary ecological water quality, we found that the percentage of urban and farmland areas had a significant ($p < 0.05$) negative correlation with the Q index-based ecological water quality of the tributary bays, and the forest cover had a marginally significant ($p = 0.058$) positive correlation with the ecological water quality. As a comparison, total nitrogen and total phosphorus in the tributary backwater regions of TGR had no reasonable correlation with the land covers within the watershed. Our study highlights that watershed management can enhance the ecological water quality in the backwater regions of TGR's tributaries, but it likely to be a long-term process. This implies considerations of other rapid measures, such as the water level regulation approach, should also be considered in reservoir management. Our study underscores the importance of ecological water quality assessment in reservoir management and provides insights into the impacts of changes in watershed land covers on ecological water quality in backwater regions of TGR's tributaries.

KEYWORDS

watershed management, biological assessment, ecological status, phytoplankton, reservoir

1 Introduction

Constructing dams and reservoirs is a significant approach for human beings to utilize and manage water resources (Wang et al., 2022). Undoubtedly, reservoir provides essential functions in providing water supply, irrigation, regulating floods, and clean hydropower generation, thereby supporting the developments of society and economy (Winton et al., 2019; Hanazaki et al., 2022). Dammed reservoirs contribute to about 30–40% of global agriculture irrigation water, and reservoir-related hydropower accounts for more than 16% of global power generation (Maavara et al., 2020). Moreover, approximately 70% of rivers on Earth are dammed and formed reservoirs according to relevant statistics (Kummu and Varis, 2007). Furthermore, globally, the construction of reservoirs is still in a rapid development period owing to the increased demands for water resource (Lehner et al., 2011; Mulligan et al., 2020).

However, the building of reservoirs is likely to lead various ecological and environmental issues including eutrophication and algal blooms, caused by alterations in hydrological situations (Fu et al., 2010; Gamez et al., 2019). Such problems are particularly pronounced in backwater areas of reservoir tributaries, where nutrients can have an extended residence time (Ye et al., 2014; Li et al., 2020). The recognition of excessive nutrient flux from upstream watershed as a primary contributor to downstream water quality degradation has been long-established in the literature (Carpenter et al., 1998; Li et al., 2021). Watershed land covers are considered a critical factor in determining nutrient export to downstream water bodies (Conley et al., 2009; Wei et al., 2020; Yin et al., 2021; Su et al., 2022; Zhang et al., 2022). Conversion of natural land covers to farmland or urban areas will increase nutrient export, which can degrade the water quality of the downstream water bodies (Huang et al., 2022; Su et al., 2022). Therefore, accurately evaluating the water quality of reservoirs and examining relationships among water quality and watershed land covers are essential for effective management of watersheds in reservoir regions.

The improvement of reservoir water quality through current knowledge has primarily relied on watershed management techniques (Komatsu et al., 2010; Shen et al., 2022). However, recent research has highlighted the effects of water level fluctuations and reservoir ecosystem characteristic itself on the water quality (Akongyuure and Alhassan, 2021; He et al., 2023). For instance, Naselli-Flores and Barone (2005) reported that the water level fluctuation is a significant factor driving water quality in Mediterranean reservoirs. Meanwhile, plankton and fish in reservoir ecosystems also have a significant impact on the biogeochemical cycle of biogenic elements, thereby influencing the water quality of reservoirs (Akongyuure and Alhassan, 2021; Xu et al., 2022). Given this, we pose the question that whether watershed land cover management alone is sufficient to enhance the water quality of reservoirs.

Beyond the chemical parameters-based water quality indices (e.g., nitrogen, phosphorus), there has been increasing focus on ecological water quality and its significance in environmental management (Karr, 1993; Katsiapi et al., 2016; Çelekli and Lekesiz, 2021). Phytoplankton, which is sensitive to environmental changes and forms the basis of aquatic ecosystems (Winder and Sommer, 2012; Ye et al., 2019), is a kind of biota widely used for evaluating ecological water quality (Padisak et al., 2006; Katsiapi et al., 2016). As the ecological status of water body gains more attention, several indices based on different groups of aquatic organisms have been established for the assessment of ecological water quality in recent years. Among them, the Q index (Padisak et al., 2006), rooted on the functional structure of phytoplankton community, is one of the most widely used indexes in assessing the ecological water quality for different water bodies with no geographic limitations (Çelekli and Lekesiz, 2021; Korneva and Solovyeva, 2021; Wu et al., 2023). Despite the growing interest in assessing the ecological water quality of lakes and reservoirs (European Environment Agency, 2000; Katsiapi et al., 2016), there has been little attention paid to the potential impacts of watershed land covers changes on ecological water quality.

The Three Gorges Reservoir (TGR) represents the largest strategic freshwater resource pool in China with a reservoir capacity of 39.3 × 10^9 m^3 (Zhang and Lou, 2011; Ye et al., 2014). Unfortunately, most backwater regions in the TGR's tributaries are facing the problems of eutrophication and phytoplankton blooms after the reservoir impoundment, as a results of reduced water velocity and the influx of excessive nutrients from the upstream watershed (Fu et al., 2010; Ye et al., 2014; Luo et al., 2022). Although watershed land covers management has long been considered a fundamental measure for water quality improvement, the impacts of watershed land cover changes in the TGR region on the water quality of backwater regions of tributaries is seldom addressed. Moreover, the evaluation of water quality for the TGR was largely relied on chemical parameters (e.g., total nitrogen and total phosphorus) (e.g., Zhang et al., 2019; He et al., 2023). Yet, the ecological water quality based on biological indicators was seldom addressed in the TGR.

The present study aims to fill the above gaps by 1) investigating the ecological water quality of tributaries and mainstream (former Yangtze River) of the whole TGR from the Three Gorges Dam to the upstream; 2) examining potential effects of changes in land covers withing watershed on ecological water quality of the backwater regions of TGR's tributaries by testing the hypotheses that increase of anthropologic activities (e.g., urbanization, farming) will deteriorate the ecological water quality (H1) and restoration of natural land cover (e.g., forest, grassland) can enhance the ecological water quality in the backwater regions of TGR's tributaries (H2); 3) discussing potential management measures that could enhance the ecological water quality of TGR and other similar reservoirs.

2 Materials and methods

2.1 Study area

The TGR is a crucial project for the developing and utilizing of water resource in the Yangtze River. From a geographical perspective, TGR is suited upstream of Yangtze River from Sandouping in Hubei province to Jiangjin County in Chongqing municipality (Xiang et al., 2021). The climate of the TGR area is the subtropical monsoon climate. The average annual air temperature of this area is 17.4°C, and the mean annual precipitation is 1204 mm (Cui et al., 2022). And the mean annual runoff of the TGR is 4.0 × 10^{11} m^3 (Yan et al., 2021).

Since the completion of the final impounding stage in October 2010, the TGR reached the design water level of 175 m, creating a massive reservoir spanning approximately 660 km in the mainstream of the Yangtze River, with a flood control capacity of 2.215 × 10^{10} m^3 (Cui et al., 2022). Typically, the lowest water levels (around 145 m) occur in late May for flood control, while the highest water levels (around 175 m above sea level) are usually observed in October (Ye et al., 2022).

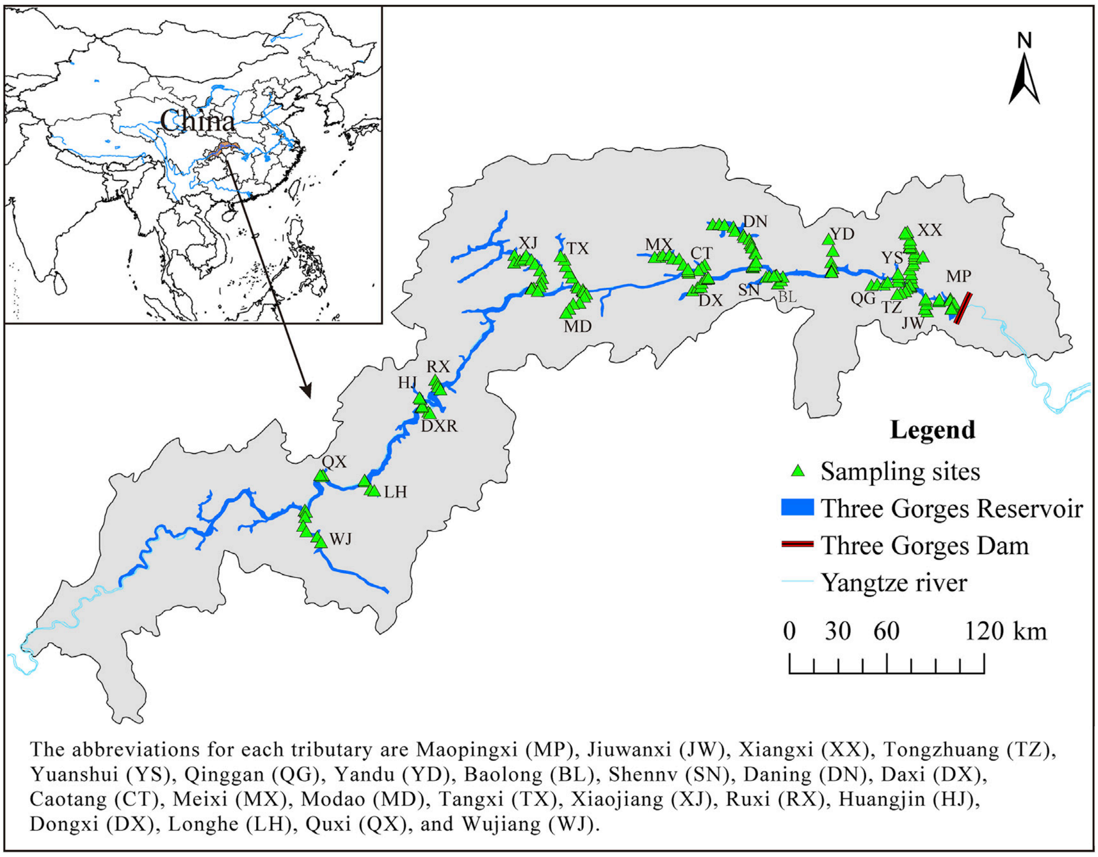

FIGURE 1
Locations of tributary bays and sites in the Three Gorges Reservoir. The polygon with grey color is the geological boundary of the Three Gorges Reservoir Region.

Because of the increased water level, downstream areas of the tributaries to the main channel of TGR in this region were flooded as the bay areas. Consequently, the watersheds for the flood tributaries formed by the impoundment of the TGR were divided into the Three Gorges Reservoir Region (Figure 1), which is the priority area for watershed management of the TGR (Zhang and Lou, 2011).

2.2 Field sampling and data analysis

In order to conduct a thorough evaluation for the ecological water quality of TGR, a total of 173 sampling sites were selected to cover 22 tributary bays and 17 transects in the mainstream of TGR, providing a full coverage of the major tributaries and mainstream of former Yangtze River of the TGR (Figure 1). Specifically, in the reservoir area in Hubei province, there are 7 tributaries and 6 transects in the mainstream of TGR (Figure 1). While the reservoir area in Chongqing province contains 15 tributaries and 11 transects in the mainstream of TGR. The field sampling was carried out on 14–25 April 2015. Due to the loss of a few phytoplankton and water quality samples, a total of 164 sampling sites were ultimately used in our study.

All field sampling and lab analyses strictly followed the standard protocols of the Chinese Ecosystem Research Network (Cai, 2007). Prior to laboratory analysis, the samples for water quality and phytoplankton were collected using a 5-L Van Dorn sampler at a depth of 0.5 m underwater. Water chemistry samples were obtained using polyethylene bottles that had been pre-cleaned and stored in dark and cool environment before lab analyses. Total nitrogen (TN) and total phosphorus (TP) used in this study were analyzed using a segmented flow analyzer (Skalar San^{++}, Netherlands). A 600 ml water sample was filtered through Whatman filter (−1.2 μm, GF/C) to measure the concentration of Chlorophyll-*a* (Chl-*a*), using by the trichromatic method from APHA (1998).

For phytoplankton enumeration and identification, 1.2-L water sample was collected and preserved with neutral Lugol's solution immediately in each site after sampling. The phytoplankton sample for each site was concentrated by the sedimentation method and then preserved with 4% formalin. Taxonomic identification of phytoplankton samples was carried out using the Fuchs-Rosenthal slide with an Olympus CX21 microscope at 10 × 40 magnification, with references to the works of Hu and Wei (2006) and John et al. (2002).

2.3 Ecological water quality assessment

The Q index, developed by Padisak et al. (2006), was used to evaluate the ecological water quality in the present study. The Q

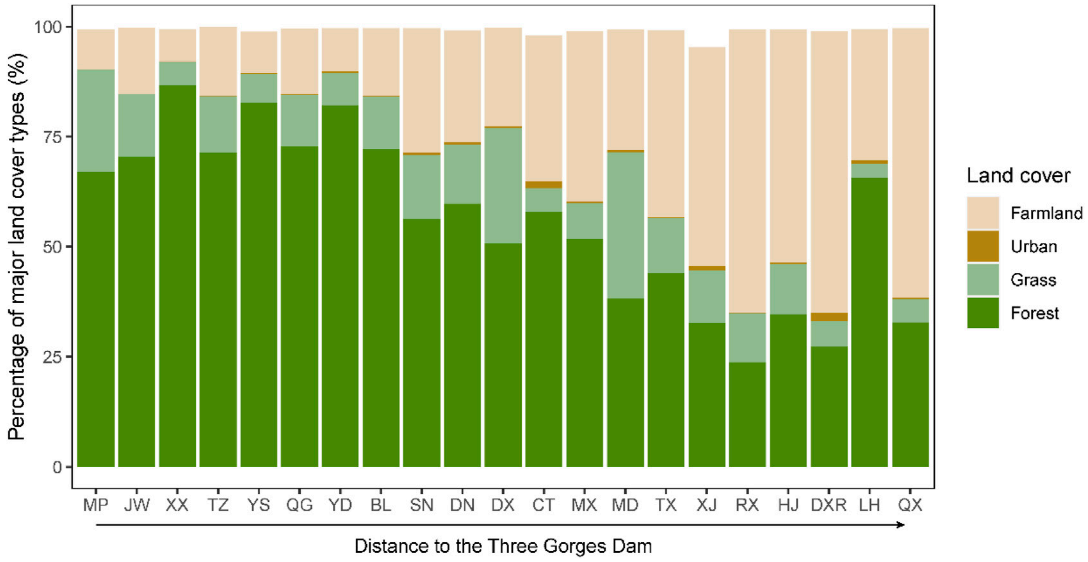

FIGURE 2
Percentage of farmland, urban, grass, and forest area of different tributary watersheds in the Three Gorges Reservoir Area. The tributaries were sorted according to their distances from the Three Gorges Dam.

index is rooted on the functional groups of the phytoplankton community and is calculated as follows:

$$Q = \sum_{j=1}^{n} p_j F$$

Here, p_j is the proportion of the biomass of the j-th functional group to the entire phytoplankton biomass for the sample; and F is the factor number for the functional group in a given water body. The resulting Q index values can be ranged from 0 to 5 and can be divided into 5 grades: bad ($0<Q\leq1$), poor ($1<Q\leq2$), moderate ($2<Q\leq3$), good ($3<Q\leq4$), and excellent ($4<Q\leq5$). The phytoplankton functional group-based Q index is a widely accepted index for the evaluation of reservoir ecological water quality worldwide (Becker et al., 2010; Wang et al., 2011; Shen et al., 2014; Korneva and Solovyeva, 2021; Çelekli and Lekesiz, 2021; Wu et al., 2023).

Here, the determinations of functional groups and the F factor mainly referred to the previous research carried out in the TGR by Wang et al. (2011). The details of phytoplankton species and the corresponding functional groups and the values of F factor could be found in Supplementary Table S1 in the supporting material. By utilizing the Q index, we are able to perform a comprehensive assessment of the ecological water quality of TGR and examine potential effects of changes in land covers on the ecological water quality of the tributary bays of TGR.

2.4 Land cover

The land cover data were obtained from the Resource and Environment Science and Data Center (RESDC) (https://www.resdc.cn). Specifically, the data of land covers were interpreted from the Landsat images by specialists in RESDC. These images were captured around the same time as our field sampling. The land cover data were aggregated into 5 categories including forest, farmland, grassland, urban area, and others, to align with our research aims.

To determine the specific land cover information for each tributary bay of TGR, we extracted the watershed outline for each tributary of TGR using QSWAT (Dile et al., 2022). Then, the area of each type of land covers in the watershed was counted to investigate potential effects of changes in watershed land covers on the ecological water quality.

3 Results

3.1 Land cover

Our study revealed that forest and farmland were the predominant land cover types in all watersheds of the tributaries located within the Three Gorges Reservoir Region (Figure 2). Specifically, the forest area ratios in all tributary watershed of TGR ranged from 23.84% to 86.72%, while the farmland ratios ranged from 7.36% to 64.25%. Notably, we observed a higher proportion of forest area in the watersheds of tributaries near the Three Gorges Dam, which decreased as the distance from the Three Gorges Dam increased (Figure 2). Conversely, the ratios of farmland area exhibited an opposite pattern, with lower percentages in the tributary watersheds near the dam and higher ratios in the tributary watersheds away from the dam. The coverage of grass was lower than that of forest and farmland, with values ranging from 3.16% to 33.31%.

TABLE 1 Statistics summary of the main water chemistry parameters in the tributary bays (n = 42) and mainstream (n = 122) in the Three Gorges Reservoir.

Category	Parameter	Mean	Range	Standard deviation
Tributary Bays	TN (mg/L)	1.689	0.687–3.519	0.501
	TP (mg/L)	0.094	0.011–0.339	0.065
	Chl*a* (μg/L)	12.47	0.17–125.60	19.69
Mainstream	TN (mg/L)	1.911	1.440–2.185	0.168
	TP (mg/L)	0.122	0.100–0.148	0.016
	Chl*a* (μg/L)	0.78	0.03–2.16	0.44

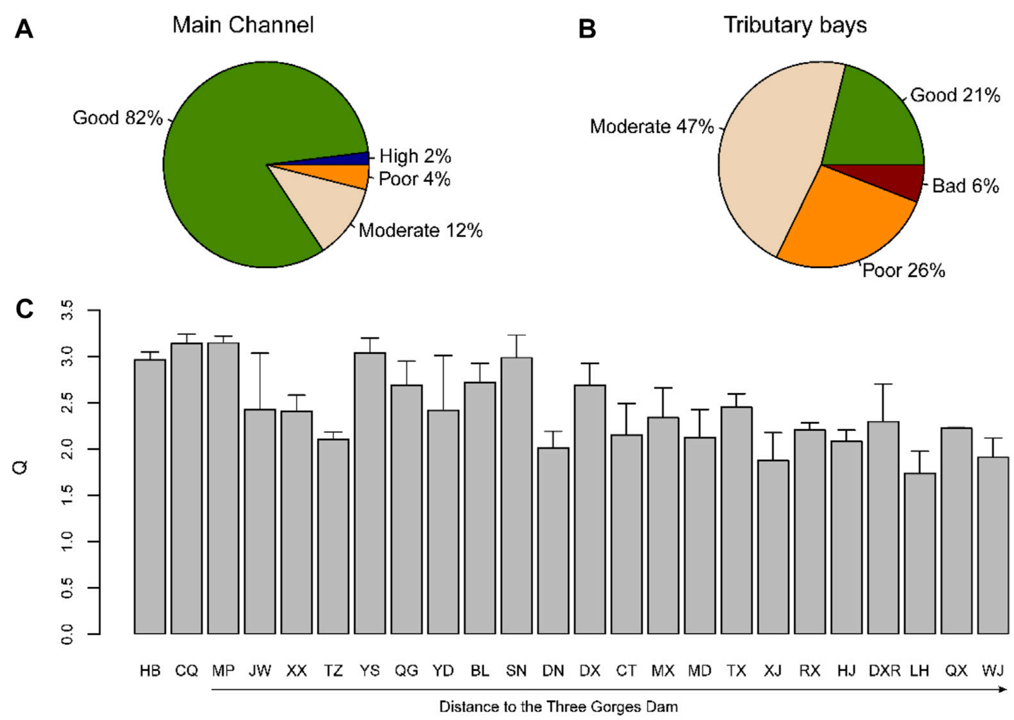

FIGURE 3
Q index-based ecological water quality assessment of the tributary bays and mainstream of Three Gorges Reservoir in Hubei province (HB) and Chongqing municipality (CQ). **(A)**: the overall ecological water quality of the main channel of TGR; **(B)**: the overall ecological water quality of the tributary bays of TGR; **(C)**: the bar plot of Q index for the mainstream and tributary bays. The tributaries were sorted according to their distances from the Three Gorges Dam. The error bar is 1 standard error.

Furthermore, the proportion of urban area in the tributary watersheds of TGR was extremely low, ranging from 0.02% to 1.81%.

3.2 Chemical characteristics

The statistical summaries for the main chemical parameters were presented in Table 1. The average concentrations of TN and TP within the backwater regions of TGR's tributaries were 1.689 and 0.094 mg/L, both of which are marginally lower than the corresponding averaged values observed in the mainstream of TGR. The averaged concentration of Chl-*a* in the tributary area was 12.47 μg/L, which is significantly higher than the mean value (0.78 μg/L) in the mainstream of TGR. Moreover, for the tributaries, we found the variations of water quality parameters in tributary bays are higher than the values in the main channel (Table 1).

3.3 Ecological water quality

The Q index-based assessment showed that the ecological water quality of most sites in the main channel of TGR are good, while most sites in the backwater regions of TGR's tributaries exhibit a status with moderate or bad ecological water quality (Figure 3). Specifically, the ecological water quality assessment found that 84% of the sampling sites in the main channel of TGR exhibited good or high ecological water quality, whereas 12% and 4% of the sites falling into moderate and poor status, respectively (Figure 3A). In contrast, only 21% of the sites in the tributary bays were in good status, with

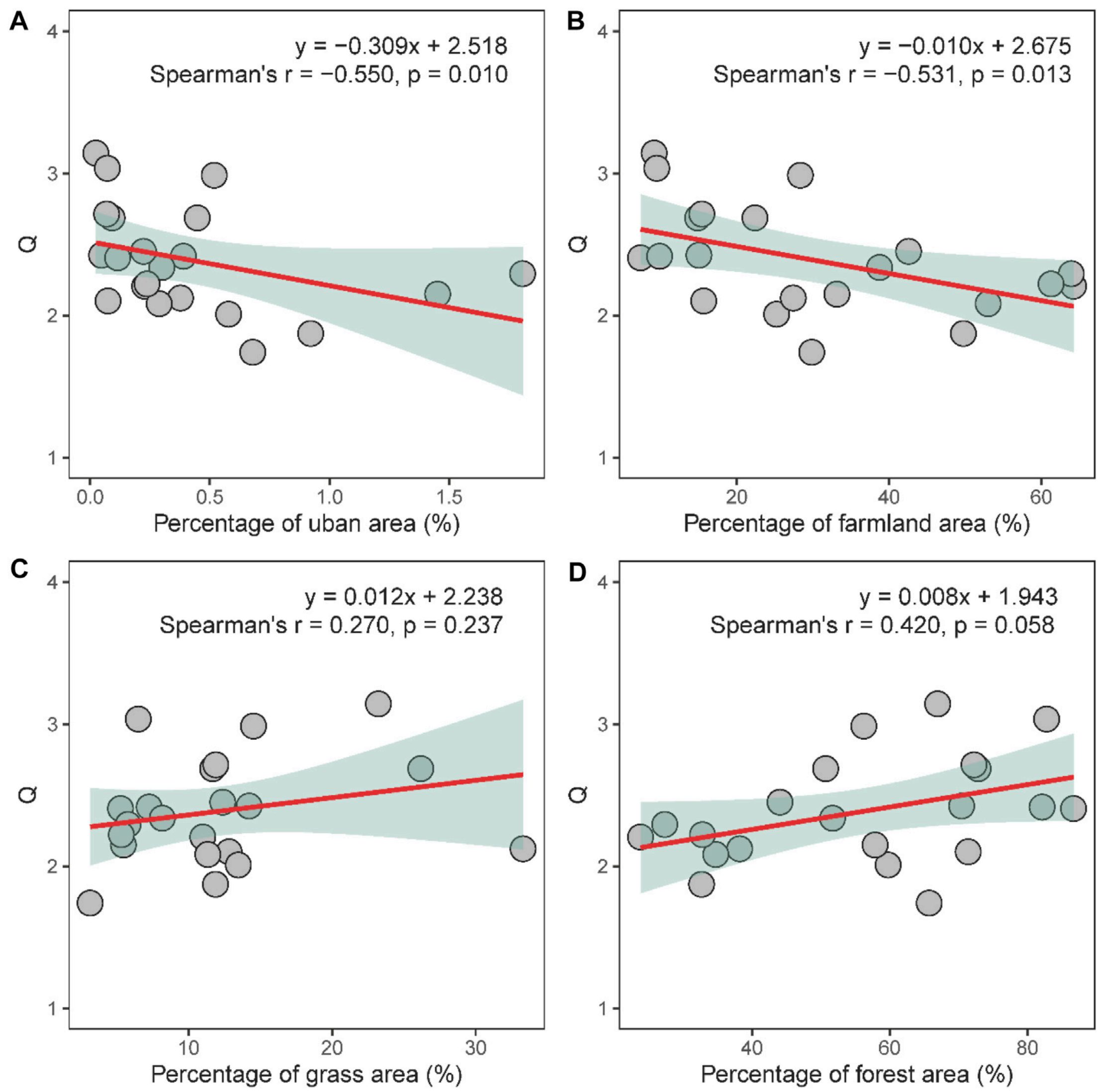

FIGURE 4
Relationships between the ecological water quality (Q) of the tributary bays and their watershed land covers [**(A)**: Urban area, **(B)** Farmland area, **(C)** Grass area, **(D)** Forest area]. The red lines denote the regression line, while the shaded areas represent the 95% confidence interval.

47%, 26%, and 6% of sites exhibiting moderate, poor, and bad ecological water quality, respectively (Figure 3B). Notably, we found that the tributary bays close to the Three Gorges Dam exhibit a better ecological water quality than the bays in the upstream (Figure 3C). Overall, the ecological water quality of tributary bays degraded with the distance from the Three Gorges Dam.

3.4 Relation between land cover and tributary ecological water quality

We found that the percentages of farmland and urban areas had significant negative correlations with the Q index-based ecological water quality of the tributary bays (Figure 4A, B). This finding supports our hypothesis that an increase in the urban and farmland area will degrade the ecological water quality in the backwater regions of TGR's tributaries (H1). On the other hand, our study did not fully support the hypothesis based on the natural land cover (H2), as the percentage of grass area had a nonsignificant positive correlation with the ecological water quality (Figure 4C). However, the percentage of forest area had a marginally significant ($p = 0.058$) positive correlation with the ecological water quality (Figure 4D), suggesting increasing forest area may improve the ecological water quality in the backwater regions of TGR's tributaries.

4 Discussion

4.1 Tributary bays are key areas for the reservoir water quality management

Here, we evaluated the ecological water quality of TGR and examined the effects of changes in watershed land covers on ecological water quality in the backwater regions of TGR's

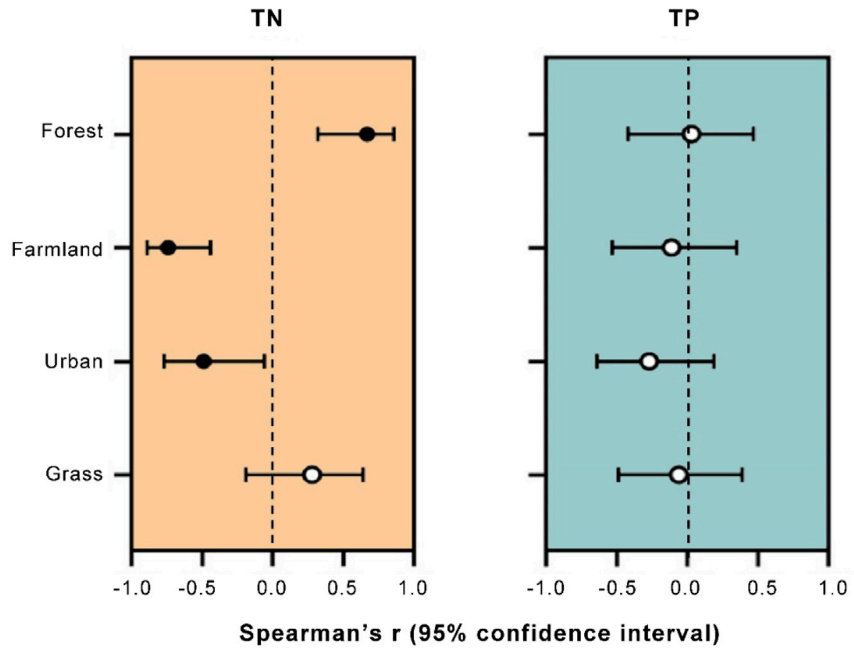

FIGURE 5
Spearman correlation between watershed land cover and the concentration of TN and TP in tributary bays of Three Gorges Reservoir. Solid circle denotes a significant correlation, while open cycle indicates a non-significant correlation.

tributaries. With the aid of the Q index, we have gained a comprehensive understanding of the ecological water quality of the entire TGR. Our investigation indicated that the ecological water quality of most regions within the mainstream (previously known as the Yangtze River) of TGR is good, while the water quality problem primarily manifests in the backwater regions of tributary bays. This finding is in accordance with the previous study based on Carlson's trophic state index (Xu et al., 2010; Tan et al., 2014) as well as the reported algal blooms in the Three Gorges Reservoir Region (Ouyang et al., 2021; Xu et al., 2021; Ye et al., 2022). From the perspective of ecological water quality, our study highlights the significance of managing the reservoir water quality in the backwater regions of TGR's tributaries.

4.2 Water quality and watershed land cover relationships

Water quality is a crucial aspect of ensuring the health and safety of our environment and public health (Su et al., 2022). The accurate assessment of water quality of a given water body is an essential concern for the successful management and protection of water resources (European Environment Agency, 2000; Cosgrove and Loucks, 2015; Bhateria and Jain, 2016; Zhang et al., 2022). Compared to the traditional chemical water quality indices such as TN and TP, our study found that Q index-based ecological water quality can better indicate the land cover changes in the watersheds of TGR's tributaries.

In our study, we observed a robust association among ecological water quality in the backwater regions of TGR's tributaries and the land covers within the corresponding watershed. However, we did not observe a reasonable correlation between the concentrations of TN or TP in the tributary bays of TGR and the watershed land cover (Figure 5). Specifically, the Spearman correlation analyses indicated that the concentrations of TP had nonsignificant relationships with watershed land cover (Figure 5). While, TN was significantly negatively correlated with the urban and farmland area, and had a significant positive correlation with the forest area. Nevertheless, the relationship between TN and watershed land cover is a spurious correlation as it is inconsistent with the common relationship observed in the TGR region, where watershed with high farmland and urban development tends to have more exports of TN and TP (Ye et al., 2009; Zhang et al., 2019; Huang et al., 2022).

The lack of a reasonable correlation between the concentrations of TN and TP and watershed land cover in the tributary bays of TGR (Figure 5) indicates that these chemical water quality indices may be susceptible to be affected by other factors, such as water level fluctuation in the TGR. Recent studies from the field observation (Xiang et al., 2021) and the hydrodynamic model (Luo et al., 2022) have supported this point, showing that water quality in the backwater regions of TGR's tributaries is mainly dominated by the backwater from the mainstream of the TGR. In contrast to traditional water quality indices, the Q index developed from phytoplankton functional composition (Padisak et al., 2006), can provide a more comprehensive and integrated assessment of ecological water quality in aquatic ecosystems because the biological assessment can measure the long-term effects of environmental changes on ecosystems (Prasse et al., 2015; Gecheva et al., 2023). Our study underscores the utility of the Q index in assessing ecological water quality in reservoir ecosystems.

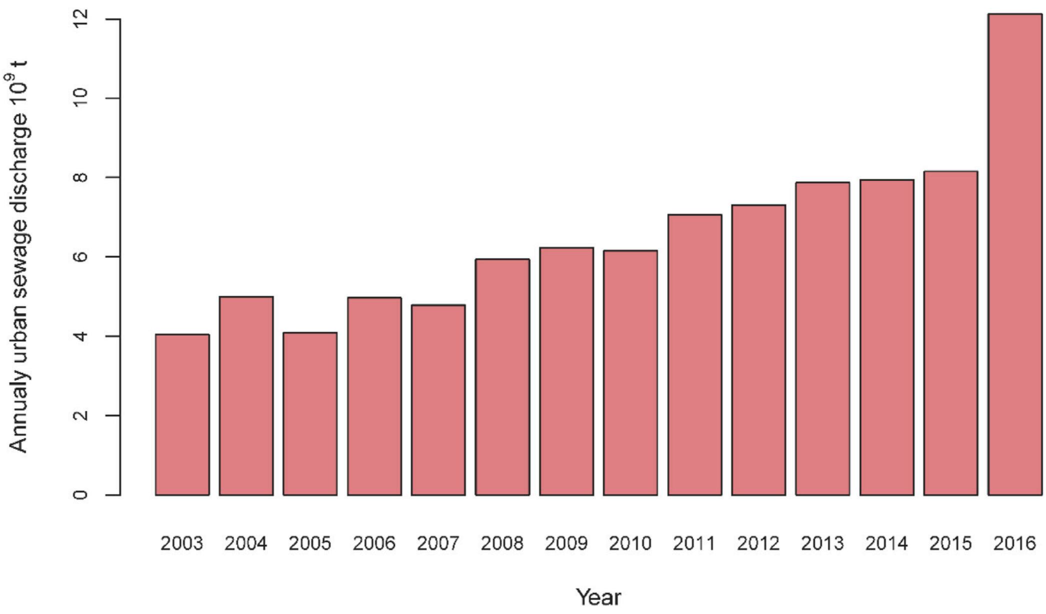

FIGURE 6
Annually urban sewage discharge in the Three Gorges Reservoir Region from 2003 to 2016.

4.3 Implication for reservoir management

Our study has several implications for the management of water quality in reservoirs. One essential implication for reservoir management is that our study revealed that appropriate watershed management can improve the ecological water quality in the backwater regions of TGR's tributaries. Specifically, the control the development of farmland and urban and increase forest area can improve the ecological water quality in the backwater regions of TGR's tributaries (Figure 4). The Three Gorges Reservoir Region is a key area for the socio-economic development of the Yangtze River Economic Belt. However, this region is still undergoing high-speed development. According to the public bulletins from the government (China National Environmental Monitoring Centre, 1998-2016), the total yearly urban sewage discharge in the TGR Region ranged from 4.04×10^9 t to 12.12×10^9 t from the year 2003–2016 (Figure 6). Meanwhile, this region is also the key area for ecological and environmental protection for the backwater regions of TGR's tributaries. In light of these facts, it is essential to implement appropriate watershed management measures to improve the ecological water quality in the backwater regions of TGR's tributaries. Our study found that watershed management is an effective approach to enhance the ecological water quality in the backwater regions of TGR's tributaries, but given the flat slope (Figure 4), this is likely to be a long-term process. Therefore, our study recommends exploring both short and middle-term approaches to improve the ecological water quality of TGR, in addition to the long-term watershed management measures.

Another implication is that the reservoir management practices should take into account the potential environmental and ecological impacts associated with fluctuations in the water levels of the reservoir. Our study showed that the land cover in the tributary watershed can significantly affect the ecological water quality in the tributary bay (Figure 4); however, the explanatory power of land cover changes to the ecological water quality appears to be limited, suggesting backwater from the mainstream of TGR would affect the ecological water quality in the tributary bays. This point was also supported by Xiang et al. (2021), which reported that the water quality (e.g., TN, TP) in the tributaries of TGR was mainly affected by the backwater movement from the mainstream of TGR, which was driven by the water level fluctuations. Meanwhile, research also showed that the water level fluctuation in reservoirs will drive the development of phytoplankton blooms in the backwater region in the Xaingxi Bay of TGR (Ye et al., 2022), which might pose a series of environmental and ecological problems (Anderson et al., 2012; Amorim and Moura, 2021). Given all the above concerns, our study suggests that effective reservoir management should also consider the impacts of water level fluctuations.

Finally, our study highlights the practicality of biological assessment in effective reservoir management. Compared to the classical water chemical indexes (e.g., TN, TP), we found that the phytoplankton functional group-based Q index can better indicate the watershed land cover changes. This result presents the advantages of biological assessment, which is sensitive to environmental changes and measures long-term effects (Prasse et al., 2015; Gecheva et al., 2023). In light of the above facts, the biotic index has been suggested as a fundamental measurement in assessing the ecological water quality by the Water Framework Directive of Europe (European Environment Agency, 2000) and the US Environmental Protection Agency (Barbour et al., 1999). And our study indicates Q index is a useful biotic index in assessing reservoir ecological water quality and has important value in water resources management.

5 Conclusion

In this study, we have investigated the ecological water quality of the whole TGR and further examined the effects of changes in watershed land covers on the ecological water quality in the backwater regions of tributary bays of TGR. The major findings of our research are as follows:

1) The ecological water quality in the mainstream (previously known as the Yangtze River) of TGR is good, while the bad ecological water quality was generally observed in the tributary bays.
2) Increase of urban or farmland area in the tributary watershed will degrade the ecological water quality in the backwater regions of the tributary bays. On the contrary, the concentrations of TP and TN in the tributary bays of TGR had no reasonable correlation with the watershed land cover.
3) Watershed management can improve the ecological water quality in the backwater regions of TGR's tributaries to some extent, but it is a long-term process based on the relationships between land cover and ecological water quality. For this reason, we suggest that effective reservoir management should also consider other rapid approaches, such as the water level regulation approach.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

LY: Conceptualization, Methodology, Formal analysis, Writing, Funding acquisition KC: Data Curation, Formal analysis JC: Data Curation, Visualization LT: Investigation, Data Curation MZ: Investigation XZ: Data Curation, Visualization QC: Conceptualization, Funding acquisition.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1196089/full#supplementary-material

References

Akongyuure, D. N., and Alhassan, E. H. (2021). Variation of water quality parameters and correlation among them and fish catch per unit effort of the Tono Reservoir in Northern Ghana. *J. Freshw. Ecol.* 36, 253–269. doi:10.1080/02705060.2021.1969295

Amorim, C. A., and Moura, A. d. N. (2021). Ecological impacts of freshwater algal blooms on water quality, plankton biodiversity, structure, and ecosystem functioning. *Sci. Total Environ.* 758, 143605. doi:10.1016/j.scitotenv.2020.143605

Anderson, D. M., Cembella, A. D., and Hallegraeff, G. M. (2012). Progress in understanding harmful algal blooms: Paradigm shifts and new technologies for research, monitoring, and management. *Annu. Rev. Mar. Sci.* 4, 143–176. doi:10.1146/annurev-marine-120308-081121

APHA (1998). *Standard methods for examination of the water and wastewater*. 20th ed. Washington, D.C: American Water Works Association, and Water Pollution Control Federation.

Barbour, M. T., Gerritsen, J., Snyder, B. D., and Stribling, J. B. (1999). Rapid bioassessment protocols for use in streams and wadeable rivers: Periphyton, benthic macroinvertebrates, and fish. Available at: https://www3.epa.gov/region1/npdes/merrimackstation/pdfs/ar/AR-1164.pdf.

Becker, V., Caputo, L., Ordóñez, J., Marcé, R., Armengol, J., Crossetti, L. O., et al. (2010). Driving factors of the phytoplankton functional groups in a deep Mediterranean reservoir. *Water Res* 44, 3345–3354. doi:10.1016/j.watres.2010.03.018

Bhateria, R., and Jain, D. (2016). Water quality assessment of lake water: A review. *Sustain. Water Resour. Manag.* 2, 161–173. doi:10.1007/s40899-015-0014-7

Cai, Q. (2007). *Protocols for standard observation and measurement in aquatic ecosystems*. Beijing: Chinese Environmental Science Press.

Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N., and Smith, V. H. (1998). Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecol. Appl.* 8, 559–568. doi:10.1890/1051-0761(1998)008[0559:Nposww]2.0.Co;2

Çelekli, A., and Lekesiz, Ö. (2021). Limno-ecological assessment of lentic ecosystems in the Western Mediterranean basin (Turkey) using phytoplankton indices. *Environ c c Sci. Pollut. Res.* 28, 3719–3736. doi:10.1007/s11356-020-10697-0

China National Environmental Monitoring Centre (1998-2016). *Bulletin of ecological and environmental monitoring of the three Gorges project in the Yangtze River*. Beijing: Ministry of Environmental Protection of the People's Republic of China ((in Chinese).

Conley, D. J., Paerl, H. W., Howarth, R. W., Boesch, D. F., Seitzinger, S. P., Havens, K. E., et al. (2009). Controlling eutrophication: Nitrogen and phosphorus. *Science* 323, 1014–1015. doi:10.1126/science.1167755

Cosgrove, W. J., and Loucks, D. P. (2015). Water management: Current and future challenges and research directions. *Water Resour. Res.* 51, 4823–4839. doi:10.1002/2014WR016869

Cui, T., Chen, X., Zou, X., Zhang, Q., Li, S., and Zeng, H. (2022). State of the climate in the three Gorges region of the Yangtze River basin in 2020. *Atmos. Ocean. Sci. Lett.* 15, 100112. doi:10.1016/j.aosl.2021.100112

Dile, Y., Srinivasan, R., and George, C. (2022). QGIS 3 interface for SWAT (QSWAT3). Available at: https://swat.tamu.edu/media/116653/qswat3-manual_v15.pdf.

European Environment Agency (2000). Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for Community action in the field of water policy. OJ L327. Available at: https://www.eea.europa.eu/policy-documents/directive-2000-60-ec-of (Accessed December 22, 2000).

Fu, B. J., Wu, B. F., Lü, Y. H., Xu, Z. H., Cao, J. H., Niu, D., et al. (2010). Three Gorges project: Efforts and challenges for the environment. *Prog. Phys. Geogr. Earth Environ.* 34, 741–754. doi:10.1177/0309133310370286

Gamez, T. E., Benton, L., and Manning, S. R. (2019). Observations of two reservoirs during a drought in central Texas, USA: Strategies for detecting harmful algal blooms. *Ecol. Indic.* 104, 588–593. doi:10.1016/j.ecolind.2019.05.022

Gecheva, G., Stankova, S., Varbanova, E., Kaynarova, L., Georgieva, D., and Stefanova, V. (2023). Macrophyte-based assessment of upland rivers: Bioindicators and biomonitors. *Plants* 12, 1366. doi:10.3390/plants12061366

Hanazaki, R., Yamazaki, D., and Yoshimura, K. (2022). Development of a reservoir flood control scheme for global flood models. *J. Adv. Model. Earth Syst.* 14, e2021MS002944. doi:10.1029/2021ms002944

He, W., Feng, S., Bi, Y., Jiang, A., Li, Y., Huang, W., et al. (2023). Influences of water level fluctuation on water exchange and nutrient distribution in a bay: Evidence from the Xiangxi Bay, Three Gorges Reservoir. *Environ. Res.* 222, 115341. doi:10.1016/j.envres.2023.115341

Hu, H., and Wei, Y. (2006). *The freshwater algae of China — systematics, taxonomy and ecology*. Beijing: Science Press.

Huang, C., Zhao, D., Fan, X., Liu, C., and Zhao, G. (2022). Landscape dynamics facilitated non-point source pollution control and regional water security of the Three Gorges Reservoir area, China. *Environ. Impact Assess. Rev.* 92, 106696. doi:10.1016/j.eiar.2021.106696

John, D. M., Whitton, B. A., and Brook, A. J. (2002). *The freshwater algal flora of the British Isles — an identification guide to freshwater and terrestrial algae*. Cambridge: Cambridge University Press.

Karr, J. R. (1993). Defining and assessing ecological integrity: Beyond water quality. *Environ. Toxicol. Chem.* 12, 1521–1531. doi:10.1002/etc.5620120902

Katsiapi, M., Moustaka-Gouni, M., and Sommer, U. (2016). Assessing ecological water quality of freshwaters: PhyCoI—a new phytoplankton community index. *Ecol. Inf.* 31, 22–29. doi:10.1016/j.ecoinf.2015.11.004

Komatsu, H., Kume, T., and Otsuki, K. (2010). Water resource management in Japan: Forest management or dam reservoirs? *J. Environ. Manag.* 91, 814–823. doi:10.1016/j.jenvman.2009.10.011

Korneva, L. G., and Solovyeva, V. V. (2021). Dynamics of morphofuncitonal groups of phytoplankton in the Rybinsk resrevoir and assessment of the resevoir water quality by the community index. *Water Resour.* 48, 65–72. doi:10.1134/S0097807821010206

Kummu, M., and Varis, O. (2007). Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River. *Geomorphology* 85, 275–293. doi:10.1016/j.geomorph.2006.03.024

Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., et al. (2011). High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Front. Ecol. Environ.* 9, 494–502. doi:10.1890/100125

Li, N. X., Wang, J., Yin, W., Jia, H. Y., Xu, J. F., Hao, R., et al. (2021). Linking water environmental factors and the local watershed landscape to the chlorophyll a concentration in reservoir bays. *Sci. Total Environ.* 758, 143617. doi:10.1016/j.scitotenv.2020.143617

Li, Y. P., Nwankwegu, A. S., Huang, Y. A., Norgbey, E., Paerl, H. W., and Acharya, K. (2020). Evaluating the phytoplankton, nitrate, and ammonium interactions during summer bloom in tributary of a subtropical reservoir. *J. Environ. Manag.* 271, 110971. doi:10.1016/j.jenvman.2020.110971

Luo, W., Luo, X., Lu, J., and Bo, M. (2022). Contribution of the reservoir backflow to the eutrophication of its tributary: A case study of the Xiangxi River, China. *Hydrology Res.* 53, 467–482. doi:10.2166/nh.2022.122

Maavara, T., Chen, Q., Van Meter, K., Brown, L. E., Zhang, J., Ni, J., et al. (2020). River dam impacts on biogeochemical cycling. *Nat. Rev. Earth Environ.* 1, 103–116. doi:10.1038/s43017-019-0019-0

Mulligan, M., van Soesbergen, A., and Saenz, L. (2020). GOODD, a global dataset of more than 38,000 georeferenced dams. *Sci. Data* 7, 31. doi:10.1038/s41597-020-0362-5

Naselli-Flores, L., and Barone, R. (2005). Water-level fluctuations in mediterranean reservoirs: Setting a dewatering threshold as a management tool to improve water quality. *Hydrobiologia* 548, 85–99. doi:10.1007/s10750-005-1149-6

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, 340. doi:10.3390/w13030340

Padisak, J., Borics, G., Grigorszky, I., and Soroczki-Pinter, E. (2006). Use of phytoplankton assemblages for monitoring ecological status of lakes within the water framework directive: The assemblage index. *Hydrobiologia* 553, 1–14. doi:10.1007/s10750-005-1393-9

Prasse, C., Stalter, D., Schulte-Oehlmann, U., Oehlmann, J., and Ternes, T. A. (2015). Spoilt for choice: A critical review on the chemical and biological assessment of current wastewater treatment technologies. *Water Res.* 87, 237–270. doi:10.1016/j.watres.2015.09.023

Shen, H., Li, B., Cai, Q., Han, Q., Gu, Y., and Qu, Y. (2014). Phytoplankton functional groups in a high spatial heterogeneity subtropical reservoir in China. *J. Gt. Lakes. Res.* 40, 859–869. doi:10.1016/j.jglr.2014.09.007

Shen, Z., Zhang, W., Peng, H., Xu, G., Chen, X., Zhang, X., et al. (2022). Spatial characteristics of nutrient budget on town scale in the Three Gorges Reservoir area, China. *Sci. Total Environ.* 819, 152677. doi:10.1016/j.scitotenv.2021.152677

Su, F., Li, P., and Fida, M. (2022). Dominant factors influencing changes in the water quantity and quality in the Dianshi Reservoir, East China. *Hum. Ecol. Risk Assess. An Int. J.* 28, 387–407. doi:10.1080/10807039.2022.2053355

Tan, L., Cai, Q., Zhang, H., Shen, H., and Ye, L. (2014). Trophic status of tributary bay aggregate and their relationships with basin characteristics in a Large, subtropical dendritic Reservoir, China. *Fresenius Environ. Bull.* 23, 650–659.

Wang, J. D., Walter, B. A., Yao, F. F., Song, C. Q., Ding, M., Maroof, A., et al. (2022). GeoDAR: Georeferenced global dams and reservoirs dataset for bridging attributes and geolocations. *Earth Syst. Sci. Data* 14, 1869–1899. doi:10.5194/essd-14-1869-2022

Wang, L., Cai, Q., Tan, L., and Kong, L. (2011). Phytoplankton development and ecological status during a cyanobacterial bloom in a tributary bay of the Three Gorges Reservoir, China. *Sci. Total Environ.* 409, 3820–3828. doi:10.1016/j.scitotenv.2011.06.041

Wei, W., Gao, Y. N., Huang, J. C., and Gao, J. F. (2020). Exploring the effect of basin land degradation on lake and reservoir water quality in China. *J. Clean. Prod.* 268, 122249. doi:10.1016/j.jclepro.2020.122249

Winder, M., and Sommer, U. (2012). Phytoplankton response to a changing climate. *Hydrobiologia* 698, 5–16. doi:10.1007/s10750-012-1149-2

Winton, R. S., Calamita, E., and Wehrli, B. (2019). Reviews and syntheses: Dams, water quality and tropical reservoir stratification. *Biogeosciences* 16, 1657–1671. doi:10.5194/bg-16-1657-2019

Wu, Z., Wang, F., Wang, X., Li, K., and Zhang, L. (2023). Water quality assessment using phytoplankton functional groups in the middle-lower Changjiang River, China. *Limnologica* 99, 126056. doi:10.1016/j.limno.2023.126056

Xiang, R., Wang, L., Li, H., Tian, Z., and Zheng, B. (2021). Water quality variation in tributaries of the three Gorges reservoir from 2000 to 2015. *Water Res.* 195, 116993. doi:10.1016/j.watres.2021.116993

Xu, H., Yan, M., Long, L., Ma, J., Ji, D., Liu, D., et al. (2021). Modeling the effects of hydrodynamics on thermal stratification and algal blooms in the Xiangxi bay of three Gorges reservoir. *Front. Ecol. Evol.* 8, 610622. doi:10.3389/fevo.2020.610622

Xu, Y., Cai, Q., Han, X., Shao, M., and Liu, R. (2010). Factors regulating trophic status in a large subtropical reservoir, China. *Environ. Monit. Assess.* 169, 237–248. doi:10.1007/s10661-009-1165-5

Xu, Y. P., Wang, L., Tang, Q. H., Naselli-Flores, L., Jeppesen, E., and Han, B. P. (2022). The relationship between phytoplankton diversity and ecosystem functioning changes with disturbance regimes in tropical reservoirs. *Ecosystems*. doi:10.1007/s10021-022-00791-4

Yan, H., Zhang, X., and Xu, Q. (2021). Variation of runoff and sediment inflows to the Three Gorges Reservoir: Impact of upstream cascade reservoirs. *J. Hydrology* 603, 126875. doi:10.1016/j.jhydrol.2021.126875

Ye, L., Cai, Q., Liu, R., and Cao, M. (2009). The influence of topography and land use on water quality of Xiangxi River in Three Gorges Reservoir region. *Environ. Geol.* 58, 937–942. doi:10.1007/s00254-008-1573-9

Ye, L., Cai, Q., Zhang, M., and Tan, L. (2014). Real-time observation, early warning and forecasting phytoplankton blooms by integrating *in situ* automated online sondes and hybrid evolutionary algorithms. *Ecol. Inf.* 22, 44–51. doi:10.1016/j.ecoinf.2014.04.001

Ye, L., Chang, C.-W., Matsuzaki, S.-I. S., Takamura, N., Widdicombe, C. E., and Hsieh, C.-h. (2019). Functional diversity promotes phytoplankton resource use efficiency. *J. Ecol.* 107, 2353–2363. doi:10.1111/1365-2745.13192

Ye, L., Tan, L., Wu, X., Cai, Q., and Li, B. L. (2022). Nonlinear causal analysis reveals an effective water level regulation approach for phytoplankton blooms controlling in reservoirs. *Sci. Total Environ.* 806, 150948. doi:10.1016/j.scitotenv.2021.150948

Yin, Z., Duan, R., Li, P., and Li, W. (2021). Water quality characteristics and health risk assessment of main water supply reservoirs in Taizhou City, East China. *Hum. Ecol. Risk Assess. An Int. J.* 27, 2142–2160. doi:10.1080/10807039.2021.1958670

Zhang, J., Li, S. Y., Dong, R. Z., Jiang, C. S., and Ni, M. F. (2019). Influences of land use metrics at multi-spatial scales on seasonal water quality: A case study of river systems in the three Gorges reservoir area, China. *J. Clean. Prod.* 206, 76–85. doi:10.1016/j.jclepro.2018.09.179

Zhang, Q., and Lou, Z. (2011). The environmental changes and mitigation actions in the Three Gorges Reservoir region, China. *Environ. Sci. Policy* 14, 1132–1138. doi:10.1016/j.envsci.2011.07.008

Zhang, Z., Guo, Y., Wu, J., and Su, F. (2022). Surface water quality and health risk assessment in taizhou city, zhejiang province (China). *Expo. Health* 14, 1–16. doi:10.1007/s12403-021-00408-6