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Tempo-Spatial Analysis of Water Quality in the Three Gorges Reservoir, China, after its 175-m Experimental Impoundment

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Abstract The Three Gorges Reservoir (TGR) has brought great socio-economic benefits and has had huge effects on the aquatic environment. The large scale and diversity of the TGR result in the variations of the water quality among the mainstream and its tributaries. Comprehensive understanding of the water quality status is crucial for water management and regional development of the TGR. Monthly data of 8 water quality parameters, including potential of hydrogen, biochemical indexes and nutrients indexes, were collected from 14 sampling sites distributed in the Yangtze River and four tributaries. The temporal and spatial distributions of each water quality parameter were presented, and the underlying causes were disclosed. The cluster analysis (CA) and the Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) were adopted to analyze and assess the water quality statuses and trend. The results showed that most of the water quality parameters presented significant seasonal patterns due to the seasonality of hydrologic/hydraulic variables. Water quality status and pollution type varied among the mainstream and its tributaries, due to the spatial heterogeneity of geology, geomorphology and anthropogenic activities. NO_3-N, TN and TP were identified as the key pollution indexes, presenting the enriched nutrients in the water body. A large proportion of NO_3-N in the TN (over 80%) was linked to the abuse of chemical fertilizers. The water quality in the TGR cannot always reach natural or desirable levels at several of the sampling sites where development and urbanization are relatively high,

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such as those near the main urban area of Chongqing or the inflow section of the Wu River. This study is expected to have major implications for water quality analysis and assessment approaches and water environment protection and management at large scales.

1 Introduction

The Three Gorges Project, the largest hydro-engineering project in the world, contributes greatly to socio-economic benefits in China, including flood control, water supply, electricity generation, navigation, etc. (Fu et al. 2010; Zhao 2013; Temoka et al. 2016; Shi et al. 2017). The mainstream backwater zone of the Three Gorges Reservoir (TGR) is approximately 660 km long and 1.1 km wide on average at the designed operational water level of 175 m, forming a typical rivertype reservoir from the Three Gorges Dam up to the Jiangjin District in Chongqing Municipality (Wu et al. 2003). Since its first impoundment in 2003, the hydrological regime has significantly changed in the TGR, such as decreased flow velocity, increased water levels, extended water retention time, stratified water temperature, and trapped sediments (Zhang and Lou 2011; Ma et al. 2015). The new hydrological regime provides unfavorable conditions for the migration and diffusion of pollutants but favorable environmental conditions for algae growth, which has led to a more complicated aquatic environment than ever before (Li et al. 2013; Yang et al. 2015). Currently, water quality degradation has been the top concern of the TGR region, and eutrophication tends to threaten the sustainable development of the region. Studies on the variations and evolution trends of water quality under the new situation are crucial and urgently needed for sustainable management of the water resources of the TGR.

The construction and development of the ecological and environmental monitoring network provides abundant data for the research of resources and environment. It is a big challenge to gain reliable and valuable information about the ecological environment through effective analysis of large amounts of monitoring data. Data-driven approaches are more practical to effectively cope with water quality data at large scale, excavating potential water quality problems and identifying the probable causes (Caballero et al. 2012; Zhai et al. 2014; Du et al. 2017). Multivariate statistical approaches, including correlation matrix, factor/principal component analysis (FA/PCA), cluster analysis (CA) and discriminant analysis (DA), have been used in the Gomti River, India (Singh et al. 2004), the Ebro River, Spain (Bouza-Deaño et al. 2008), the Coruh River Basin, Turkey (Bilgin and Konanç 2016), the Huai River Basin, China (Zhai et al. 2014; Wang et al. 2017), etc. Various types of water quality indexes have been developed as concise and convenient tools to express water quality (Gao et al. 2016). Water quality indexes vary because of the differences in the characteristics of statistical integration and interpretation of parameter values, all of which have advantages and limitations (Lumb et al. 2011). The Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) is an objective-based index that compares observed values of water quality parameters to guideline or standard values (Hurley et al. 2012). The CCME-WQI has good flexibility in the selection of water quality parameters and benchmarks, and shows extensive adaptability to assess the water quality of rivers, lakes and reservoirs (Mohebbi et al. 2013; Yan et al. 2016). Researchers have obtained reliable and

useful information about the water quality from the evaluation and interpretation of large complex data sets. Water quality status and probable causes can be revealed by identifying the underlying relationships among variables.

Several studies have been conducted on the environmental status and future trends of the water regime in the TGR (Li et al. 2013). Zhao et al. (2013) assessed the water quality in the inlet (Zhutuo) and outlet (Yichang) of the TGR from 2006 to 2011. Tang et al. (2015) performed a temporal and spatial investigation in the tributary bays of the TGR. Zhao et al. (2016) researched the water quality status in the TGR using multiple analysis approaches. These studies have provided some useful information about the water quality status, but further research is still necessary because significant heterogeneity exists in such a large reservoir. The TGR has a catchment area of 64,000 km^2. It is very complex of the spatial variations of the climate, topography, soil types, vegetation covers, land uses and human activities. In addition, with the construction of the Three Gorges Dam, the hydrology and water quality processes have greatly changed in the TGR. This region flows through both urban and rural areas (Fu et al. 2010), covering more than 20 tributaries. The occurrence of algae blooms has become more frequent in tributary bays, leading to a decline in water quality and a reduction in water safety. Agricultural and mining activities in the tributary basins lead to the import of pollutants into the TGR. Tributary inflows tend to complicate the spatial and temporal trends of the water quality in the TGR (Tang et al. 2015). More representative sites are necessary to analyze the spatial and temporal variations of the water quality in the TGR and to elaborate the causes of the variations in water quality at different locations. Moreover, the major pollutant in the waterbody needs to be determined.

In this study, 8 water quality parameters, including potential of hydrogen (pH), biochemical indexes (dissolved oxygen (DO), potassium permanganate index (COD$_{Mn}$) and five-day biochemical oxygen demand (BOD$_5$)) and nutrients (total nitrogen (TN), ammonia nitrogen (NH$_3$-N), nitrous nitrogen (NO$_3$-N) and total phosphorus (TP)), from 2008 to 2014 were collected from 14 sampling sites distributed within the TGR area. The objectives of this study were to: (1) illustrate the variation in the spatial and temporal characteristics of the selected parameters, (2) explore the major factors affecting the water quality, (3) identify the key pollution indexes in the TGR, and (4) provide a concise evaluation of the water quality with an eligible water quality index.

2 Materials and Methods

2.1 Description of the Study Area and Location of Sampling Sites

The TGR is located in the upstream of the Yangtze River, stretching along the Yangtze River from Jiangjin District of Chongqing Municipality to Yichang City of Hubei Province (Fig. 1). The TGR was first fully impounded for trial in October 2008, and the full impoundment lasted approximately 5 months (from November to March of the following year). At that time, the TGR covered a total surface area of 1045 km^2 and 660 km along the backwater area when the water level reached 175 m during the dry season. The operating water level of the TGR is divided into three stages - the impounding stage (October to early February the following year) when the water level reaches 175 m, the discharging stage (late February to early May) when the water level lowered to 155 ~ 165 m, and the flood stage (May to September) when the water level lowered to 145 m (Nie et al. 2017).
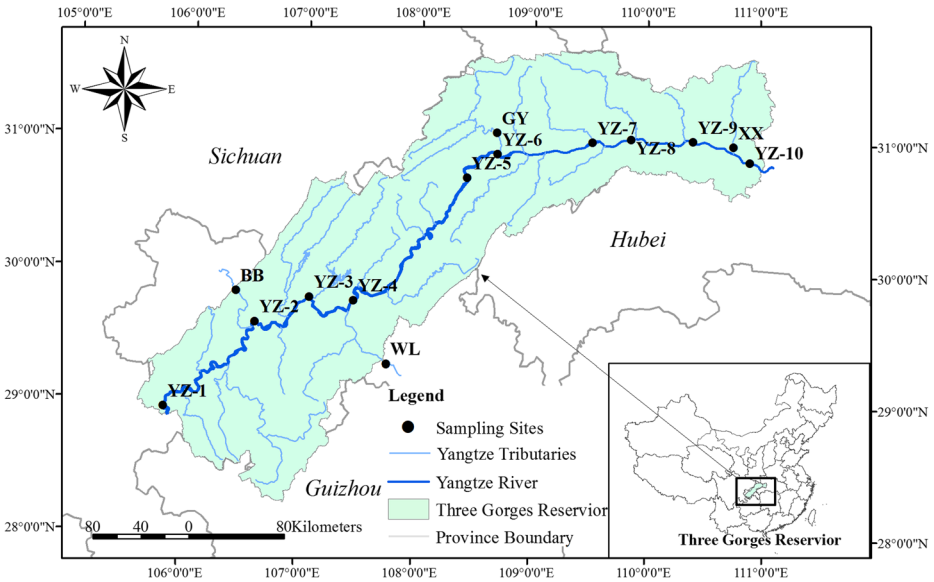
Fig. 1 Location of the TGR and the distribution of the sampling sites

The TGR area has a subtropical monsoon humid climate with four distinctive seasons. 80% of rainfall occurs between May and October affected by the summer monsoon (Ma et al. 2016). Thus, meteorological disasters such as torrential rain, floods and drought are common. The spatial variation of rainfall is influenced by the complex topography and wind circulation. The area has an average annual temperature of 17.9 °C, and the lowest and highest annual temperatures range from 6 °C to 8 °C and 27 °C to 29 °C, respectively. According to the environmental quality standards for surface waters (GB3838–2002) (Table 1) in China, the water quality in the main TGR channel during a majority of the time between 2008 and 2010 was classified as grade III with a nitrogen concentration limit of 1 mg/L and a phosphorus concentration limit of 0.05 mg/L (MEPPRC 2010, 2011).

In this study, 14 sampling sites covering the entire basin were selected (Fig. 1). They are the Zhutuo (YZ-1), Cuntan (YZ-2), Changshou (YZ-3), Qingxichang (YZ-4), Wanxian (YZ-5), Xiaojiang (YZ-6), Fengjie (YZ-7), Daning (YZ-8), Badong (YZ-9) and Miaohe (YZ-10) sections in the mainstream, the Beibei (BB) section in the Jialing River, the Wulong (WL) section in the Wu River, the Gaoyang (GY) section in the Xiaojiang River, and the Xiangxi

Table 1 Classification of water area functions in GB3838–2002. Class III: mainly for class II protected areas for centralized potable water sources and protected areas for general fishing and swimming areas. Units for water quality parameters were mg/L except pH. pH is a dimensionless parameter

Classification Standard value items	Class I	Class II	Class III[a]	Class IV	Class V
pH	6~9				
DO	7.5	6	5	3	2
COD_{Mn}	2	4	6	10	15
BOD_5	3	3	4	6	10
NH_3-N	0.15	0.5	1.0	1.5	2.0
TN	0.2	1.5	1.0	1.5	2.0
TP	0.01	0.025	0.05	0.1	0.2

(XX) section in the Xiangxi River. The major indexes of specifications of the selected tributaries are presented in Table 2.

2.2 Data Sources and Processing

The data used in this study were obtained from the Hydrology Bureau of Changjiang Water Resources Commission of the Ministry of Water Resources and Chongqing Academy of Environmental Science. Monthly data of 8 water quality parameters, including potential of hydrogen, biochemical indexes and nutrients indexes, were collected from 2008 to 2014. The water quality parameters, their units and abbreviation, as well as the methods used for their determination, are illustrated in Table 3.

2.3 Cluster Analysis

Cluster analysis (CA) is an unbiased method that discovers the intrinsic relations between samples and/or variables. The objects of the system are classified into categories or clusters according to their similar magnitudes or variations, instead of a priori assumptions (Vega et al. 1998). Hierarchical CA has been used extensively in water quality assessments, especially in the discrimination of sampling sites and the assessment of water body status (Kitsiou and Karydis 2011). The main steps of hierarchical CA are measuring the similarities (or distances) of the samples and/or variables and grouping the objects according to their similarities (or distances) by linkage algorithms. This grouping is generally exhibited as a hierarchical tree. The closeness or similarity between a pair of sampling sites is expressed by their Euclidean distance (the square root of the sum of the squared differences between the values of water quality concentrations), and the procedure for clustering is the Ward method (Ward 1963). As the objects are paired into binary clusters, the grouping process repeats until a distinct dendrogram with well-separated clusters is formed.

2.4 Canadian Council of Ministers of the Environment Water Quality Index

Water quality index methods are an effective way to bridge water quality communication gaps among scientists, policy-makers and the public. Researchers have developed various types of water quality indexes that are suitable for local conditions, and all water quality indexes have advantages and limitations (Lumb et al. 2011). Among the indexes, the CCME-WQI provides a flexible index template that is adaptable to the specificity of a site and allows scientists to select appropriate guidelines as water objectives according to their requirements (Hurley et al. 2012; Alexakis et al. 2016; Yan et al. 2016). Because of the merits of the CCME-WQI, it has been applied to assess water quality globally by many agencies, receiving high evaluation.

Table 2 Major indexes of specifications of the selected tributaries

Tributaries name	River length (km)	Catchment area (km²)	Location	Confluence with Yangtze River
Jialing River	1120	156,142	tail area of the TGR	Chongqing City
Wu River	1037	83,035	middle region of the TGR	Fulin County
Xiaojiang River	180	5200	middle region of the TGR	Yunyang County
Xiangxi River	97	3099	head region of the TGR	Zigui County

Table 3 The water quality parameters used in the study and their abbreviations, units and methods of determination

Parameters	Abbreviations	Units	Methods
Potential of hydrogen	pH	–	GB/T 6920–86
Dissolved oxygen	DO	mg/L	GB 11913–89
Potassium permanganate index	COD_{Mn}	mg/L	GB 11892–89
Five-day biochemical oxygen demand	BOD_5	mg/L	GB 7488–87
Ammonia nitrogen	NH_3-N	mg/L	GB 7479–87
Nitrate nitrogen	NO_3-N	mg/L	GB/T 7480–87
Total nitrogen	TN	mg/L	GB 11894–89
Total phosphorus	TP	mg/L	GB 11893–89

The CCME provides detailed information regarding index calculation and application (CCME 2001, 2006). The index scores are calculated as follows:

$$CCME-WQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right) \tag{1}$$

where F_1 (scope) represents the percentage of the water quality parameters that do not meet their respective guidelines at least once during the period considered (failed water quality parameters), F_2 (frequency) represents the percentage of individual sample measurements (tests) that do not meet their respective guidelines in the period considered (failed tests), and F_3 (amplitude) represents the amount by which the failed measurements do not meet their respective guidelines. The value of CCME-WQI ranges from 0 to 100. Values close to 0 signify very poor water quality. Values close to 100 indicate excellent water quality. The results can be ranked in five categories: excellent (95–100), good (80–95), fair (65–79), marginal (45–64) and poor (0–44) (CCME 2001).

In our study, CCME-WQI was selected to evaluate the water quality in the TGR by using all selected water quality parameters listed in Table 3. The water quality objectives comply with the Class III standards (GB3838–2002) (Table 1). NO_3-N is not considered in the GB3838–2002. The water quality objective of NO_3-N referred to NH_3-N and TN in this paper.

3 Results and Discussion

3.1 Temporal Variation of Water Quality in the TGR

The temporal variations of the water quality parameters except pH were influenced by the seasonality of rainfall, temperature and water level (Figs. 2, 3 and 4). The time series of water quality parameters were the mean concentrations of all the sampling sites presented in Fig. 1. Different characteristics exhibited among these parameters. The pH values varied from 7.40 to 9.03, with an average of 8.08, presenting slightly alkaline characteristics of the water body in the TGR. The DO concentrations peaked in the winter and were lower in the summer. DO in the water reflects biochemical pollution levels and is significantly relevant to ambient temperature (Fig. 3). The low temperature in the winter inhibits the bioactivity of aquatic life and results in low oxygen consumption. COD_{Mn}, NH_3-N, NO_3-N, TN and TP showed similar temporal patterns that were higher in the summer and lower in the winter; however, the
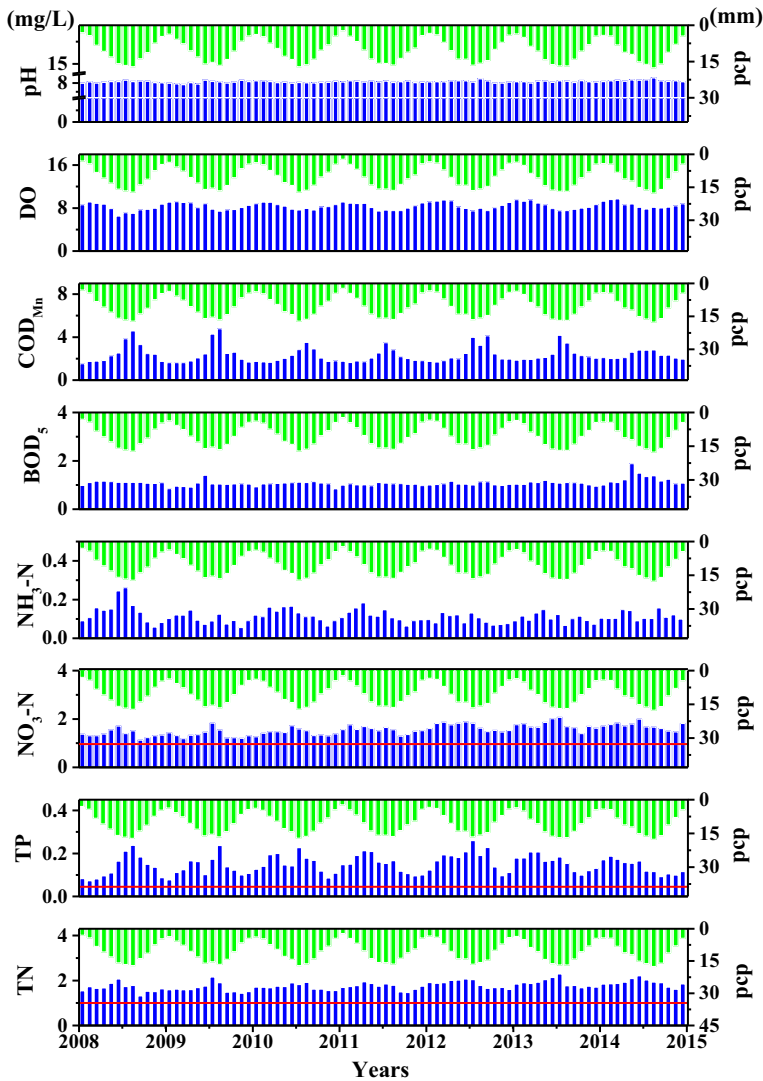
Fig. 2 Precipitation (pcp) and water quality parameters time series of the TGR from 2008 to 2014 with the level of the GB3838–2002 Class III standards (red lines, and the top five subplots have never higher than Class III)

underlying causes were rather different. The concentrations of COD_{Mn} and NH_3-N mainly originate from industrial and domestic emissions. Thus, these concentrations increased during the falling stage and decreased during the impounding period, presenting a negative relation with water level as well as water storage volume (Fig. 4). The temporal patterns of COD_{Mn} and NH_3-N are closely related to the powerful self-purification and dilution effects of the rivers. The temporal variation of TP was almost the same as those of COD_{Mn} and NH_3-N, but the affecting factors were very different. Anthropogenic pollution caused by agricultural activities and soil erosion is the main source of phosphorus, and the fluctuations in phosphorus can be attributed to the wide seasonal variations in precipitation and sediment discharge year-round (Singh et al. 2004; Xie et al. 2017). Frequent storm events in the flood season induced the vast
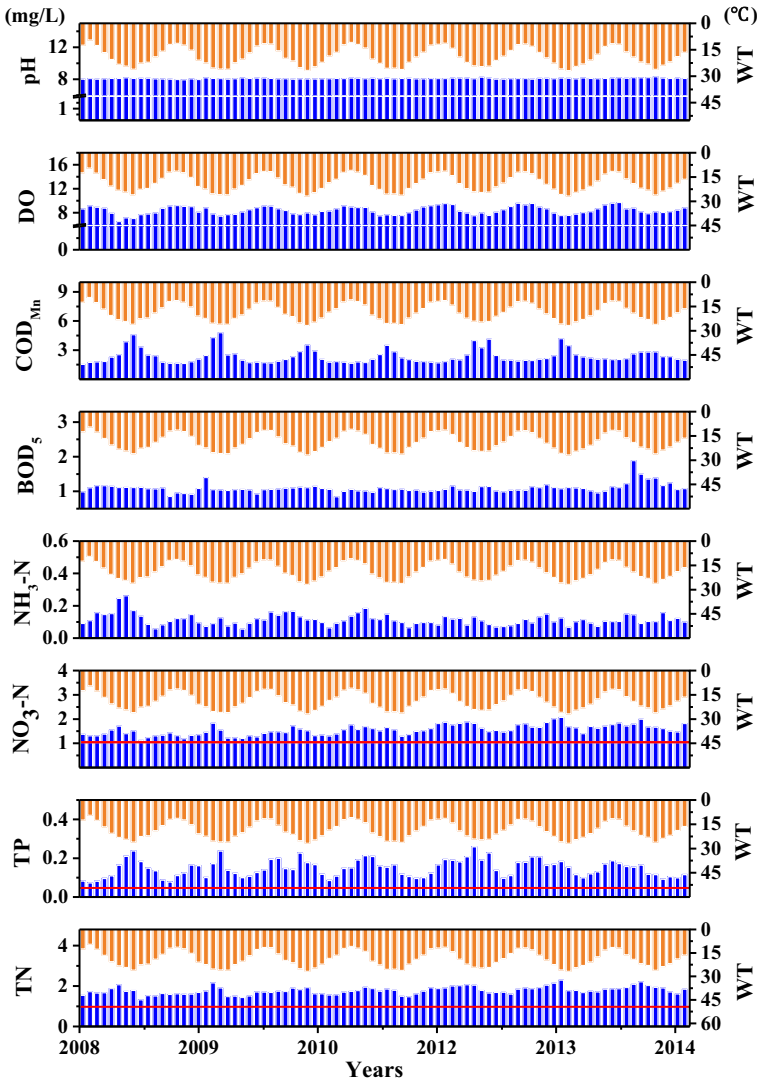
Fig. 3 Water temperature (WT) and water quality parameters time series of the TGR from 2008 to 2014 with the level of the GB3838–2002 Class III standards (red lines, and the top five subplots have never higher than Class III)

amount of suspended sediment that carried a large amount of phosphorus from upland areas into the TGR. Anthropogenic activities such as agriculture and household and municipal sewage discharges are the main sources of nitrogen in the water (Zhao et al. 2016). The complex integrated effect makes the variations of NO_3-N and TN more complicated, and these parameters showed relatively small seasonal fluctuations.

Figure 5 shows the relatively stable inter-annual variations of the water quality parameter concentrations. The concentrations of water quality parameters at all the sampling sites were used to generate Fig. 5. The lengths of the boxes indicate the inter-quartile range of the water quality parameter concentrations. The horizontal lines in the boxes represent the median
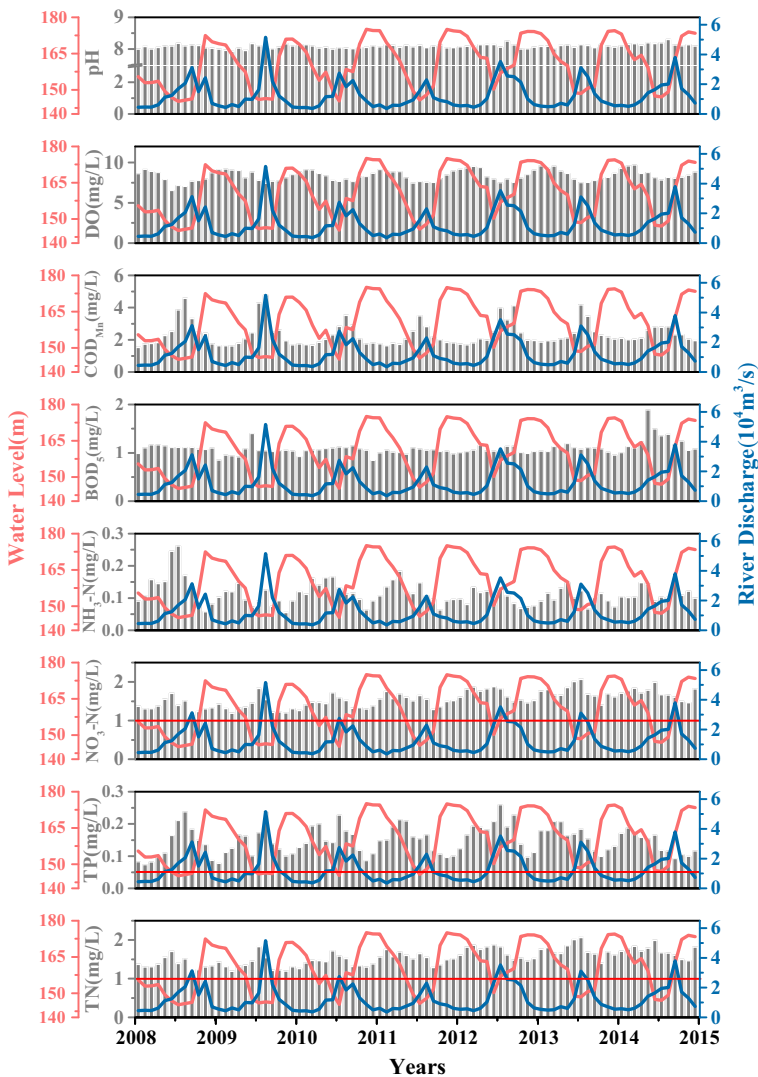
Fig. 4 Water level, river discharge and water quality parameters time series of the TGR from 2008 to 2014 with the level of the GB3838–2002 Class III standards (red lines, and the top five subplots have never higher than Class III)

concentrations of the water quality parameters, while the small box in the box charts are the mean concentrations of the water quality parameters. The median concentrations of DO, COD_{Mn}, BOD_5 and NH_3-N ranged from 8.13 to 8.54, 1.90 to 2.07, 0.9 to 0.98, and 0.09 to 0.11, respectively. It is remarkable that the mean concentrations of BOD_5 were all higher than the upper quartile. This result indicated that the concentration of BOD_5 was more sensitive and vulnerable to human activities. A slightly increasing trend of NO_3-N and TN is shown in Fig. 5. TP increased from 2008 to 2013 and then decreased in 2014. The reduction in TP concentration in 2014 was primarily attributed to the operation of the cascade hydropower stations in the upstream of the TGR.
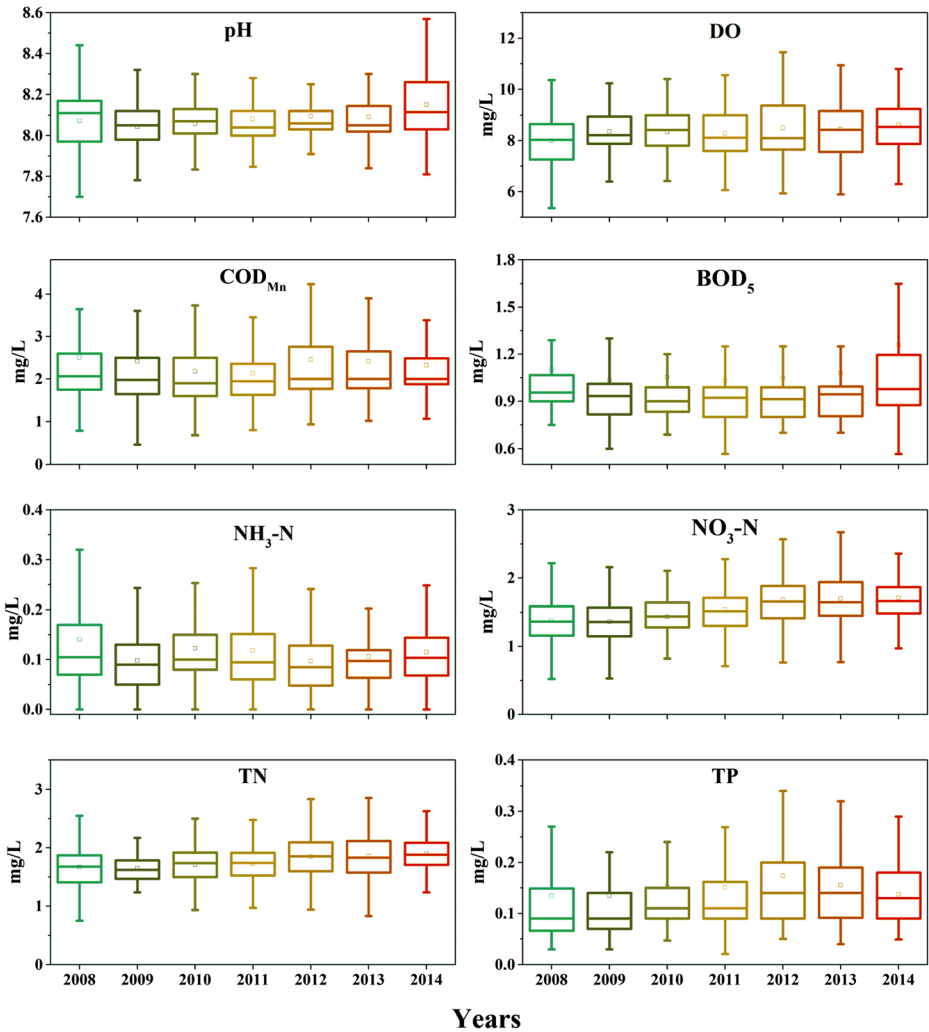
Fig. 5 Inter-annual variations of the water quality parameter concentrations from 2008 to 2014

3.2 Spatial Variation of Water Quality in the TGR

For the spatial trends, the concentrations of the water quality parameters showed different fluctuation patterns (Fig. 6). The water quality in the tributaries exhibited a wider variation than those (YZ 1–10) in the Yangtze River.

The concentrations of DO, COD_{Mn}, NH_3-N and TP decreased gradually from upstream to downstream in the Yangtze River. DO was high from YZ-1 to YZ-4, lower from YZ-5 to YZ-8, and then continued to decline at YZ-9 and YZ-10. The concentrations of COD_{Mn} and NH_3-N increased at YZ-2, and then decreased from YZ-3 to YZ-4. YZ-2 is located downstream of both the confluence zone of the Jialing River and the main urban region of Chongqing City, where the water quality is influenced by the upstream inflow of both the Yangtze River and
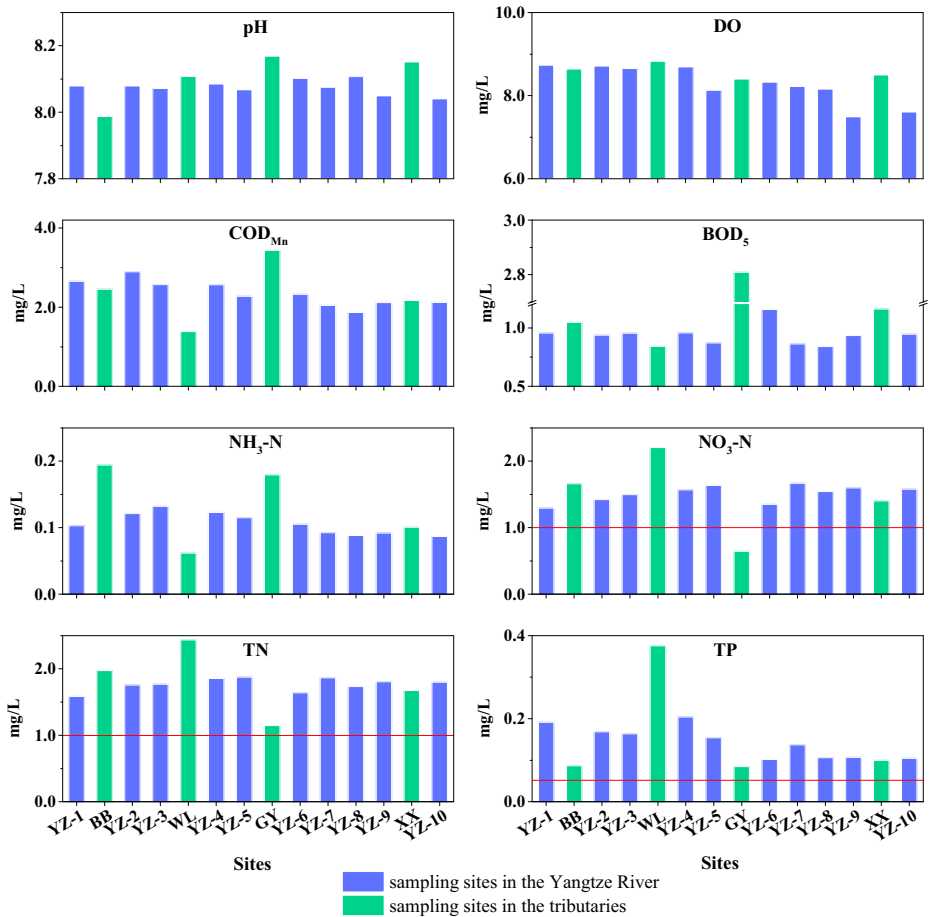
Fig. 6 Concentrations of the water quality parameters at each sampling site (from upstream the downstream) along with the levels of the GB3838–2002 Class III Standard (red lines, and the top five subplots have never higher than Class III)

Jialing River, as well as the industrial and municipal drainage system. The concentrations of TP exhibited sudden increases at YZ-4 and YZ-7. It is obvious that the concentrations of TP at the sampling sites near the reservoir tail were higher than those near the Three Gorges Dam. The concentrations of NO_3-N and TN showed fluctuations. There was a clearly increasing trend of the concentrations of NO_3-N and TN from YZ-1 to YZ-4. YZ-4 is located downstream of the confluence zone of the Wu River. The increases in the NO_3-N, TN and TP concentrations were mainly due to the inflow of the Wu River.

The spatial patterns of the water quality parameters in tributaries were more irregular and complex. High COD_{Mn} (3.44 mg/L) and BOD_5 (2.81 mg/L) concentrations occurred in the GY section, which is the monitoring station in the Xiaojiang River, while the concentrations of NO_3-N, TN and TP were relatively lower in this section. The opposite occurred in the WL section, which is the inflow section of the Wu River, and had extremely high TN (2.44 mg/L) and TP (0.38 mg/L) concentrations and low COD_{Mn} and BOD_5 concentrations. Agricultural

non-point source pollutions and phosphorus mine exploitations are intensive in the upstream basin of the Wu River in Guizhou Province (Han et al. 2016). The NH_3-N concentration in the BB section (0.19 mg/L), which is the inflow section of the Jialing River, was clearly higher than that at the other sampling sites.

The hierarchical CA produced a dendrogram that grouped the sampling sites on the based on their similarities (Fig. 7). The tree grows from left to right. The grouping process starts with all sampling sites; each group contains only one member, just like tree roots showed by horizontal lines. Then, the process continues with root growth and aggregation, and branches are gradually added to the right side of the tree. These branches continue to grow and ultimately merge into three aggregates. The top of the graph has a line of numbers, and these numbers represent the rescaled distance of each category. The number indicates the changes in the distance or similarity between classes. The number of categories varies with the rescaled distance. Fig. 7 shows that the sampling sites were finally separated into three clusters according to the pollution status of the water body and the variation of the water quality parameters. Cluster 3 contains only the GY section, which is the monitoring station in the Xiaojiang River and was classified as the low- pollution region in the TGR. The sampling sites belonging to Cluster 2 were YZ-1, YZ-2, YZ-3, and YZ-4, which are located near the main urban area of Chongqing City. The concentrations of COD_{Mn} and NH_3-N in Cluster 2 were generally higher, and the areas in Cluster 2 have been reported to be heavily polluted by industries and domestic activities on the riverbanks of the Yangtze River. The rest of the sampling sites are contained in Cluster 1 and are located in either less-developed areas along the Yangtze River or its tributaries, and these sites correspond to the characteristic of being slightly affected by human beings. It can be concluded that neighboring locations share similar water quality characteristics.

These spatial variations indicated that there were diverse pollution types at different sites because of the specificity of the large scale and diversity in the TGR. Along with the division
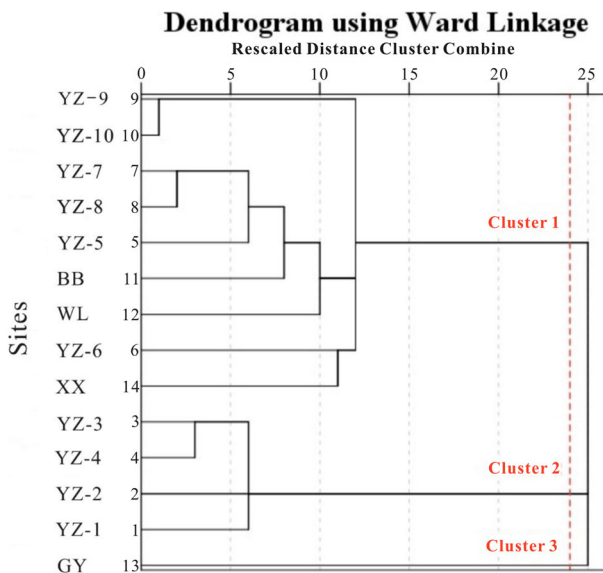

Fig. 7 Dendrogram based on agglomerative hierarchical clustering of the 14 sampling sites in the TGR

of the operation stage of the TGR, the backwater zone is enlarging; thus, the water quality has suffered from very different levels of impacts from upstream to downstream. High intensities of human intervention have made the TGR a complicated ecosystem with wide regional variations. Due to the tremendous capacity and higher flow in the Yangtze River, self-purification, the dilution effect and water exchange contribute to the pollution reductions (Temoka et al. 2016). Discharge from the tributaries between YZ-1 and the Three Gorges Dam could lead to a dilution effect or pollution effect on the mainstream. Therefore, the background concentrations of nutrients in the Yangtze River were higher than those in some tributaries, such as the Xiaojiang River and Xiangxi River. As a result, during the high water level stage of the TGR in the winter, a large amount of reservoir backwater would flow into the tributaries, and the inputted nutrients could accumulate in the tributaries and may provide sufficient nutrients for algal blooms in the spring (Gao et al. 2016).

3.3 Identification of Key Pollution Indexes in the TGR

Figures 2, 3, 4 and 6 show that the biochemical parameters, DO, COD_{Mn} and BOD_5, were at good levels and met the requirements of Class II (GB 3838–2002) most of the time. COD_{Mn} was classified Class III (GB 3838–2002) during only a single month (July in 2008, 2009 and August in 2009). However, NO_3-N, TP, and TN always exceeded the Class III standards with a nitrogen limit of 1.0 mg/L and a phosphorus limit of 0.05 mg/L in the lakes and reservoirs. It is obvious that NO_3^-N, TN and TP can be identified as the main pollution factors in the TGR, while other water quality parameters exceeded the Class III (GB3838–2002) standards at only individual intervals. It is clear that the overall water quality in the TGR remained basically stable except for the continuous deterioration of nutrients, suggesting that the TGR was exposed to the risk of not being used as drinking water storage.

According to a large amount of research, non-point source pollution from both natural and anthropogenic factors has become a main cause of water deterioration in the TGR area (Shen et al. 2015; Shi et al. 2017). Atmospheric deposition, water and soil erosion, and fertilizer and pesticides are responsible for the inputs of nitrogen and phosphorus (Li et al. 2013; Gao et al. 2016). More than 4000 km^2 of land is utilized for agricultural activities, with a high cropping index (average number of time of crops are grown in 1 year) of 2.18 and frequent tillage (MEPPRC 2015), which fosters a large amount of inputs of sediment and nutrient inputs from diffuse sources into the water bodies (Strehmel et al. 2016). A great deal of fertilizers and pesticides with low efficiencies, which are the main sources of TN and TP, are used in the highly intensive modern agriculture in the TGR area every year (Zhao et al. 2008). In 2014, 615.4 tons of pesticides were used in the TGR, including 302 tons of organophosphorus pesticides, and 130,000 tons of fertilizers were used in the TGR, including 85,000 tons of nitrogenous fertilizer and 36,000 tons of phosphate fertilizer (MEPPRC 2015). The nitrogen and phosphorus losses turned into pollutants and were transported to water bodies via rainfall and irrigation. In this study, TN was dominated by NO_3-N. The average contribution of NO_3-N to TN was over 80% in the entire TGR area. This result suggested that the NO_3-N was closely related to the regional concentration of chemical fertilizers used in agricultural activities.

The water-sediment process in the Yangtze River also plays an important role in the transportation and transformation of pollutants in the aquatic environment. Pollutants strongly interact with sediments by the combined processes of sorption/desorption and mineral precipitation/dissolution (House 2003; Kunz et al. 2011). Sediments are deposited in the riverbed along the Yangtze River, as well as the pollutants absorbed to sediments. So, the

pollutant concentrations declined in the water body (Hu et al. 2009). Previous studies have proven that sediment-associated processes involved in adsorbing or releasing nutrients such as phosphorus and ammonium actually exist in the bays of the TGR (Wang et al. 2010a, b). Similar to rainfall, sediments processes are concentrated during the flood seasons. Frequent storm events during the flood season induce a large amount of suspended sediment that carries nutrients and anthropogenic pollutants from the upland areas into the TGR (Xie et al. 2017). In fact, the annual sediment loadings often result from only a few major storms during the flood season. For example, sediment discharge in the BB section reached 12.8 million tons from10~24 September 2014, which accounted for 88.3% of the total amount of sediment transport at the station. Similarly, the WL section had 4.6 million tons of sediment discharge from 6~22 July 2014, which accounted for approximately 72.5% of the sediment discharge in the whole year. These results suggested that soil and water conservation practices should be paid special attentions during storm period.

The water-level fluctuation zone (WLFZ) resulted from periodic fluctuations of the water level ranging from 145 m to 175 m, which also led to the input of nutrients. Plants in the WLFZ are related to the nutrient cycling within the TGR, because this zone provides the nutrients for plant growth, soil absorption and the water environment (Li et al. 2013). From May to September, many plants grow in the WLFZ, accumulating nutrients from both the overlying water and sediments (Xiao et al. 2017). At the same time, the waste accumulating from the upland and upstream regions were exposed in the WLFZ. When the water level gradually increases to 175 m, the decomposition of submerged soil and plants may release large amounts of organic matter, nutrients and other waste into the water, leading to the deterioration of the water quality (Liu et al. 2004; Xiao et al. 2017). Plants in the WLFZ are also an important source of high nutrients in the summer when runoff erosion frequently occurs because of the large amounts of rainfall and stronger rainfall intensities (Ma et al. 2016).

3.4 Water Quality Assessment Using the CCME-WQI

We calculated both the spatial and temporal variations of the CCME-WQI in the TGR, and all of the water quality parameters were taken into account. The CCME-WQI values for each sampling sites from 2008 to 2014 are listed with their corresponding category in Table 4. Both the spatial and temporal assessment showed that the water quality status remained relatively steady. In general, the categorizations were ranked between marginal and fair except for the GY section, which is the monitoring station in the Xiaojiang River that was rated good from 2009 to 2011, and in 2013 and 2014, with the remaining years of 2008 (79.19) and 2012 (79.16) were ranked close to the good category. The water qualities at the sampling sites where development and urbanization were relatively high and at the site in the rural area were relatively bad. The water quality status gradually improved from upstream to downstream in the Yangtze River. The result was consistent with the former analysis in our study.

There are two opposing opinions on the impact of dam construction on the water quality of rivers. One opinion is that dams reduce the flow rate and sediment transport and block hydrological continuity, thus leading to deterioration in the water quality (Wei et al. 2009). The other opinion is that dams raise the water level in the reservoir area and prolong hydraulic residence time (the average amount of time that water spends in a particular river reach), thus increasing the self-purification capacity of the overall water resource (Ouyang et al. 2011). The calculations in this study also demonstrated that the water qualities of at YZ-5, YZ-6, YZ-7, YZ-8, YZ-9 and YZ-10 in the mainstream of the TGR were relatively better and more stable

Table 4 CCME-WQI with corresponding water quality status for the TGR during 2008–2014 (bold, underlined, and normal text correspond to the CCME-WQI category of good, fair and marginal, respectively)

Sampling sites	2008	2009	2010	2011	2012	2013	2014
YZ-1	58.81	66.72	64.74	66.26	57.30	64.68	65.06
BB	76.44	68.68	66.31	67.79	61.63	67.73	67.18
YZ-2	58.85	60.81	65.76	60.16	63.38	59.23	64.45
YZ-3	59.02	59.67	65.91	65.80	58.83	64.13	64.41
WL	62.69	62.10	54.38	53.84	54.32	55.97	60.50
YZ-4	59.00	58.72	63.70	57.96	56.90	57.04	63.61
YZ-5	65.01	59.91	64.82	65.10	63.29	63.40	65.00
GY	79.19	**83.12**	**83.79**	**82.41**	79.16	**80.35**	**80.39**
YZ-6	64.48	76.00	67.93	69.30	65.83	69.20	54.77
YZ-7	66.26	66.16	65.82	65.07	63.83	63.91	64.65
YZ-8	69.08	67.15	66.97	66.73	65.62	65.92	66.14
YZ-9	68.16	68.51	66.69	66.73	66.22	64.83	65.13
XX	70.40	70.29	67.47	68.02	67.23	66.10	60.57
YZ-10	68.74	69.06	66.86	67.12	66.04	65.07	65.02

than the water qualities at the other stations. This phenomenon was inferred to be one of the benefits of dams because of its powerful self-purification and dilution effects.

The CCME-WQI can assess the general water quality both qualitatively and quantitatively by a group of typical assessment items instead of using the worst one (single index evaluation method such as GB3838–2002). In addition, the CCME-WQI can be used to compare the water quality status of different stations of the same river or different rivers. According to our study, when combined with parameter analysis, the CCME-WQI can be easily used to assess whether the comprehensive water quality meets the specified water objectives and to give a clear determination of the water category, which is easily understood and accepted by the public. Therefore, the CCME-WQI method also becomes an appropriate approach to assess the water quality of the TGR.

4 Conclusions

This study provides comprehensive analyses of the water quality in the TGR since its 175-m experimental impoundment. Monthly data of 8 water quality parameters including pH, biochemical indexes and nutrients were collected from 14 sampling sites (ten at the Yangtze River and four at different tributaries) distributed within the TGR area from 2008 to 2014. The main conclusions were as follows:

(1) The temporal trends of the water quality parameters in the TGR were mainly controlled by seasonal factors and the operation of the TGR, while the spatial distribution varied due to the spatial heterogeneity of geology, geomorphology, the anthropogenic activities (industrial, agricultural, domestic) and economic developments in such a large basin. Water quality and pollution type varied between the mainstream and its tributaries. High concentrations of nutrients occurred in the tributaries, especially the Jialing River and Wu River. The concentrations of biochemical indexes were relatively high in the Xiaojiang River, but still at the desired level. The sampling sites were objectively divided into three groups with similar water quality characteristics by means of cluster analysis, suggesting

that the water quality in the TGR was significantly affected by anthropogenic disturbances.

(2) Owing to the ambitious plan of building waste treatment plants and strict supervision and inspection of environmental protection, point source pollutants have been effectively controlled. However, non-point source pollution is currently the primary contributor to impacts the water quality in the TGR. NO_3-N, TN and TP were identified as the key pollutant indexes in the TGR. Concentrations of these water quality parameters exceeded Class III (GB3838–2002) standards with a N limit of 1.0 mg/L and a P limit of 0.05 mg/L in lakes and reservoirs all the time. Large proportions of NO_3-N in TN were linked to the abuse of chemical fertilizers.

(3) The results of the CCME-WQI showed that the water quality in the TGR was almost ranked between marginal and fair, and presented small fluctuations. The water quality at the sampling sites where development and urbanization were relatively high, or in rural area need to be paid more attention.

The study provided useful information for water quality management in the TGR. Serious control measures are urgently needed for non-point source pollution, and the hydrologic and hydraulic conditions should be taken into account. Further investigations about the characteristics of non-point source pollution and how it affects the water quality are required for the sustainable development of the TGR.

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