

Assessing Water Quality of Three Gorges Reservoir, China, Over a Five-Year Period From 2006 to 2011

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Abstract Understanding temporal variability in water quality in the Three Gorges Reservoir (TGR) is crucial for evaluating environmental effects of damming and protecting China's largest freshwater resource. This study examined water quality changes in the main channel of the Yangtze River after dam completion as well as its relationship with water level fluctuation (WLF), controlled by annual impoundment operations and conditioned by flooding. Finally, the mass balance budget and integrative water quality indexing (WQI) methods were applied to elucidate the status of overall water quality since dam completion. Results showed that TGR outlet water (Yichang) exhibited higher pH and COD_{Mn} values and lower concentrations of dissolved oxygen (DO) and ammonia nitrogen ($\text{NH}_3\text{-N}$) than inlet water (Zhutuo). Temporal variations in water quality parameters displayed similar trends for the outlet and inlet. Water quality parameters all showed negative correlations to water level, revealing the different effects of damming on water quality. It was estimated that reservoir impoundment led to a DO depletion of $1495.5 (\pm 1482.0) \times 10^3$ tons/yr and a COD_{Mn} increase of $564.0 (\pm 405.0) \times 10^3$ tons/yr, likely deriving from various internal pollutant loads from the WLF zone and tributary watersheds. According to WQI, TGR water quality remained at healthy levels. However, WQI linear regression showed that water quality at the outlet significantly decreased over time, indicating that the construction of the Three Gorges Dam generally caused water quality deterioration. Further investigation is required to determine the spatial distribution of point and non-point pollution sources and to identify major factors that influence TGR water quality.

Keywords Internal release · Water level fluctuation · Water quality index · Three Gorges Dam

1 Introduction

Since the beginning of civilization, humans have tried to alter hydrological cycles by damming, piping, channelization and other such means to reap the benefits of the natural environment. Throughout the world, dams play an important role in promoting economic and social development, such as providing electricity (Branimarte et al. 2008; Zhang et al. 2012). The Three

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Gorges Reservoir (TGR) on the Yangtze River is by far the world's largest hydropower development project. It is also used for flood control, irrigation, navigation, and water supply. These benefits are undisputable. However, the debate over the TGR project is ongoing with regards to its adverse environmental and ecological impacts. For one, the size and scope of the project make it impossible to restore the area back to its original natural conditions (Wasimi 2010). One of the most serious consequences is believed to be the deterioration of water quality, which has proved worse than anticipated (Stone 2011).

The monitoring of water quality since completion of the dam is of great importance in assessing the effects of damming on water quality. This will aid in the optimization of the dam's water resources for proper environmental management. The management of Yangtze River water quality is crucial for the continued health of its internal aquatic ecosystem and China's South–north Water Diversion project. Conclusions derived from previous studies on aquatic environmental effects of damming are inconsistent. For instance, some researchers have suggested that the dam's adverse effects on water quality are due to a breakdown in river continuum and a decrease in water velocity (Morris and Fan 1998; Wei et al. 2009). Stow et al. (2001) and Ouyang et al. (2011) both concluded that the dam noticeably decreased water nitrogen (N) and phosphorus (P) concentrations just downstream of it. Stanley and Doyle (2002) reported that nutrient concentrations in small impoundments for other small dams were often smaller than upstream concentrations. Results from the Huai River Basin, China, reported that dams in the upper reaches played a positive role in improving water quality while dams in the middle and lower reaches played a negative role (Zhang et al. 2010). Yang et al. (2012) also attempted to find a positive role these dams play in solving environmental problems, such as preventing downstream diatom blooms in the Yangtze River Basin. However, the role of reservoirs is complex due to processes of uptake, sedimentation, and burial of silica (SiO_2) as a result of damming rivers (Teodoru et al. 2006; Sferratore et al. 2008). Using the deterministic Riverstrahler model, Sferratore et al. (2008) predicted a reduction of P and SiO_2 and an increase in N flux due to dam construction. This model can assess the respective roles of how a reservoir traps nutrients through algal uptake and sedimentation and changes in vegetation induced by flooding valleys formerly covered by forest and wetland.

Being aware of the importance of water resource management in the TGR, Chinese hydrologists and environmentalists have paid considerable attention to water quality changes since the largest freshwater impoundment operation began. For instance, Lv et al. (2007) calculated that water quality in the area of the reservoir was primarily at Grade III of China's Environmental Quality Standard for Surface Water (GB3838-2002). Chai et al. (2009) found that concentrations of dissolved inorganic N, soluble reactive P, and total N exhibited an increasing trend from 2002 to 2006 in the Yangtze River Estuary and the adjacent East China Sea. In contrast, their findings showed that total P concentrations exhibited a decreasing trend. The majority of previous studies have focused on pollution sources and loads from agriculture, industry, shipping, and sewage in tributaries around the TGR (Wang et al. 2006; Huang et al. 2007; Tullos 2009; Tian et al. 2010; Zhu et al. 2010). On the other hand, few studies have focused on water quality changes within the main channel of the Yangtze River over relatively long periods of time. In addition, little data has been published on annual TGR water quality. One reason for this knowledge gap may be that the measurement of TGR water quality is time-consuming, laborious, and costly due to the vast region that must be covered (reservoir length is 5,578 km long when water level is maintained at 175 m above mean sea level). Another reason may be that there was a broad consensus that the water quality in the main channel of the Yangtze River remained good due to the assumption of a high self-purification capacity of the reservoir. Owing to these reasons, most researchers in recent years have only focused on water quality of Yangtze River tributaries, which are

critical area in terms of their concentrated pollutant inputs and relatively closed environment (Li et al. 2009; Ye et al. 2009). Branimarte et al. (2008) reported that the decline in reservoir water quality, with increased nutrient and decreased dissolved oxygen concentrations, was related to domestic sewer plant effluents and agricultural run-off. From this perspective, the investigation and quantification of the internal contribution of the TGR should be considered when assessing water quality in the main channel of the section of the Yangtze River located within the TGR. Continuous and extensive TGR water quality monitoring is important for assessing water quality and water resource management practices in this region. In addition, the Three Gorges Dam itself creates water level fluctuations (WLF) due to seasonal dam regulations, which could adversely affect water quality. This is probably due to pollutant release processes that occur during frequent WLF zone exposure. However, the relationship between WLF and TGR water quality has received far less attention.

The objectives of this study were to (1) analyze changes in pH, dissolved oxygen (DO), chemical oxygen demand (COD_{Mn}), and ammonia nitrogen ($\text{NH}_3\text{-N}$) of TGR water as it relates to water quality indexes (WQI) before and after damming (from 2006 to 2011); (2) investigate the relationship between WLF and the four water quality parameters throughout the study period; (3) estimate the amount of DO, COD_{Mn} , and $\text{NH}_3\text{-N}$ derived from the internal release after reservoir impoundment; and (4) ascertain the general temporal trend of water quality at the TGR outlet by applying a WQI to determine whether water quality is improving or deteriorating. This study could help to accurately understand water quality change processes and help to establish sustainable management strategies for the TGR.

2 Materials and Methods

2.1 Study Area

With a total length of 6,397 km, the Yangtze River is the third largest river in the world. It was on this river that the construction of the world's largest hydroelectric project began in December 1994. The dam structure was completed at Yichang in May 2006. The Three Gorges Dam is 2,309 m long and 185 m above mean sea level. When water levels reach the designated maximum height of 175 m above mean sea level, the reservoir contains 39.3 km^3 of water and has a total surface area of $1,045 \text{ km}^2$, with a mean water depth of approximately 70 m and a maximum depth of 170 m. The TGR Region includes 21 counties with a total area of $58,000 \text{ km}^2$, including Chongqing and Yichang, with a population of 20.68 million (Meng et al. 2005). The TGR is subject to a subtropical monsoon climate with humidity levels from 60 % to 80 %. Annual average temperatures vary from $16.7 \text{ }^\circ\text{C}$ to $18.7 \text{ }^\circ\text{C}$ with an extreme maximum temperature often exceeding $41 \text{ }^\circ\text{C}$. Average annual rainfall is approximately 1,000 to 1,300 mm.

2.2 Data Description and Processing

The national surface water monitoring network is coordinated and maintained by the China National Environmental Monitoring Centre (CNEMC) (<http://www.cnemc.cn>, last accessed January 2012). In order to evaluate the effects of the Three Gorges Dam on water quality of Upper Yangtze River within TGR section, data from two CNEMC stations (an inlet station and an outlet station) were used for this study. Weekly measurements were carried out at Zhutuo, the city limit between Chongqing and Sichuan Province (TGR inlet) and Yichang in Hubei Province (TGR outlet) from 2006 to 2011 (Fig. 1). For this study, four water quality parameters (pH, DO, COD_{Mn} , and $\text{NH}_3\text{-N}$) were used to evaluate water quality changes and predict future

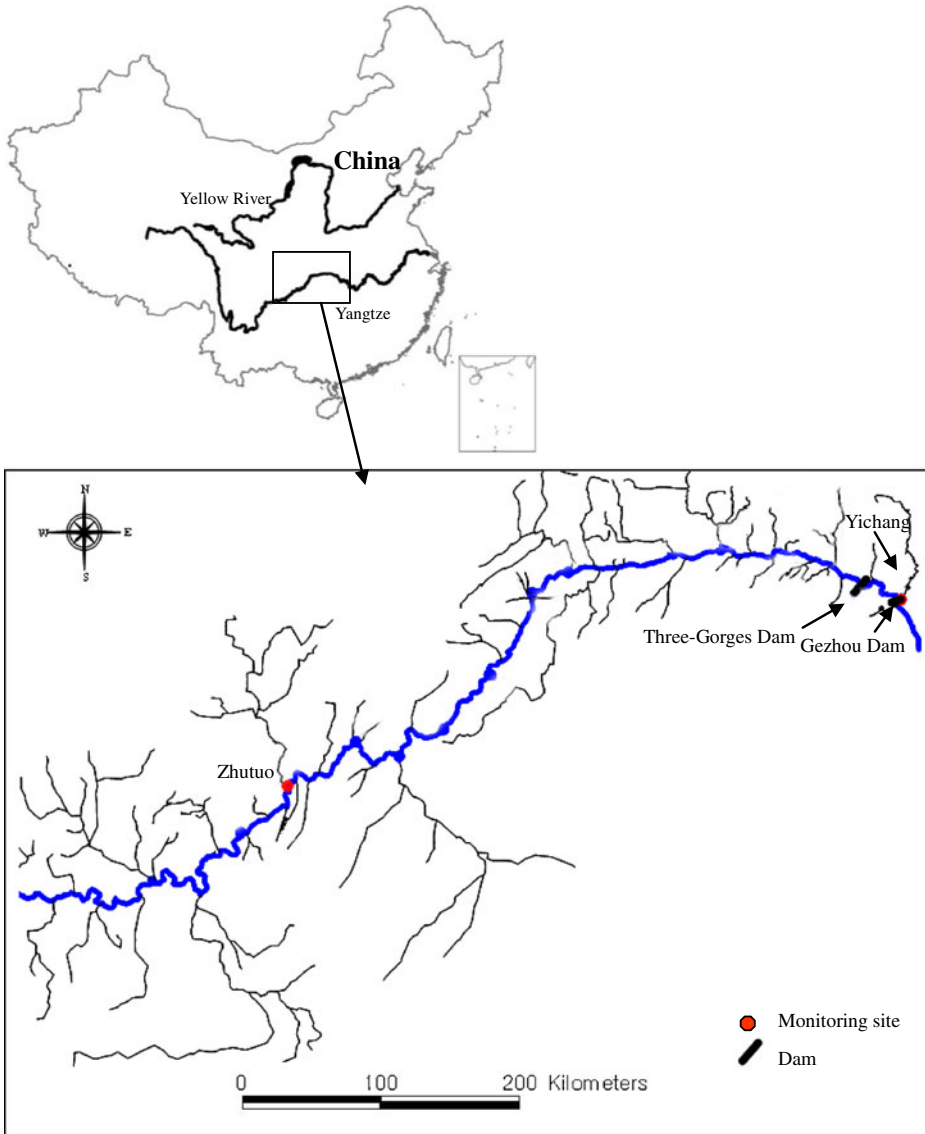


Fig. 1 Sketch map of monitoring sites and Three Gorges Dam on the Yangtze River, China

trends in TGR water. Each water quality parameter was analyzed using standard methods (Ministry of Environmental Protection of China 2002). TGR water levels and inflow and outflow data (taken at a 2-h time interval) were provided by the China Three Gorges Corporation (<http://www.ctg.com.cn/inc/sqsk.php>, last accessed January 2012). Median weekly data was used to represent water quality per week. Average water levels taken each day were also analyzed against water quality of the corresponding day.

Statistical analysis was carried out by applying one-way ANOVA with R (R Development Core Team 2012). For each variable, a time series plot was prepared (water quality variable versus time). Correlations between WLF and water quality parameters (pH, DO, COD_{Mn} , and

NH₃-N) were assessed using Pearson's correlation coefficient. Data that were not normally distributed (Shapiro–Wilk test) was log-transformed to meet the assumptions of normality necessary for Pearson's analysis.

A simple black-box method was applied for this study in order to assess the internal release capacity of pollutants from submerged plants, soils, and tributaries. Pollutant concentrations in water at the outlet were assumed to represent TGR output values, and pollutant concentrations in water at the inlet were taken as input values. Subsequently, the internal release capacity can be calculated as follows:

$$E(j) = C_o(j) \times V_i(j) + C_o(j) \times V_o(j) - C_i(j) \times V(j)_i - C_b(j-1)V_b(j-1) \quad (1)$$

$$E_T = E(1) + E(2) + \dots E(j) + \dots + E(n) \quad (2)$$

where C_o is the concentration of a specific pollutant within the outflow at the outlet; V_i is TGR water volume based on its relationship to water level (Li and Kuang 2009); C_i is the concentration of a specific pollutant within the inflow at the inlet; V_i is the inflow volume during impoundment time; C_b is the concentration of a specific pollutant before impoundment; V_b is water volume before impoundment; E_T is total pollutant release during impoundment; and n is the number of weeks impoundment takes place. $E(j)$ is the net accumulated amount of pollutant derived from internal release when impoundment starts in the TGR in the j^{th} week. If $E(j) > 0$, the internal release rate is higher than the self-purification rate; if $E(j) = 0$, the rate of internal release is equal to the self-purification rate; if $E(j) < 0$, self-purification is the dominant process occurring in the TGR.

To assess TGR water quality, four parameters (pH, DO, COD_{Mn}, and NH₃-N) were selected to calculate the minimum water quality index (WQI_{min}) for outlet water. The equation used for the subjective WQI was proposed by Rodriguez de Bassoon (Pesce and Wunderlin 2000). It is as follows:

$$WQI_{min} = k \frac{\sum_{i=1}^n C_i P_i}{\sum_{i=1}^n P_i} \quad (3)$$

where n is the total number of parameters; C_i is the value assigned to parameter i after normalization; and P_i is the relative weight assigned to each parameter. P_i values ranged from 1 to 4, with 1 assigned to the parameter that had the lowest effect (e.g., pH) and 4 assigned to the parameter that had the greatest impact on aquatic life (e.g., DO). For this study, the relative weight of COD_{Mn} and NH₃-N parameters were both assigned 3. k was the subjective constant. WQI_{min} was calculated using $k=1$ in all cases to account for variation in measured parameters. According to Kannel et al. (2007), WQI_{min} can be allocated into five ranges: 0–25 very poor, 26–50 poor, 51–70 average, 71–90 good, and 91–100 excellent. Linear fitting was used to determine the trend in TGR water quality over time by WQI_{min}.

3 Results and Discussion

3.1 Spatial Differences in Water Quality Between Inlet and Outlet

Table 1 provides statistical results of the four water quality parameters for the TGR inlet and outlet throughout 2006 and 2011. Outlet water pH ranged from 7.20 to 8.72. DO levels

Table 1 Comparison of water quality variable for TGR outlet and inlet water from 2006 to 2011

Variables	Inlet				Outlet			
	Mean	Min.	Max.	CV%	Mean	Min.	Max.	CV%
pH	7.66(0.44) ^a	6.64	8.59	5.80	8.08(0.22) ^b	7.20	8.72	2.70
DO	8.16(1.51) ^a	5.88	13.00	18.50	7.82(0.97) ^b	5.96	11.50	12.45
COD _{Mn}	1.94(0.72) ^a	0.70	4.00	37.23	2.25(0.63) ^b	0.90	4.60	28.09
NH ₃ -N	0.24(0.10) ^a	0.05	0.50	39.48	0.18(0.05) ^b	0.05	0.37	26.04

Values with different superscript letters denote significant difference at $P < 0.01$, according to unpaired t-test

varied between 5.96 and 11.50 mg/l. COD_{Mn} showed the highest variability among the four parameters investigated, ranging from 0.90 to 4.60 mg/l. NH₃-N varied from 0.05 to 0.37 mg/l. According to China's Environmental Quality Standard for Surface Water (GB3838-2002, Ministry of Environmental Protection of China 2002), the quality of TGR outlet water was classified Class II the majority of the time. Only during a single week (inundation period at the end of October, 2010) was the water classified Class III. This occurred when DO was 5.96 mg/l. The standard DO value for sustaining aquatic life is 4 and 6 mg/l for purposes of drinking (Alam et al. 2007). In general, good water quality was observed in the main channel of the Yangtze River based on the data taken from the four parameters between 2006 and 2011. However, findings were different for Lv et al. (2007) who reported that TGR water quality was primarily categorized Class III. Their study measured greater COD_{min} and NH₃-N and smaller DO levels and found that TGR water Hg concentrations exceeded the Class III standard.

Analysis from this study showed that pH and COD_{Mn} were significantly higher ($P < 0.01$) at the outlet compared to the inlet. In contrast, DO and NH₃-N exhibited significantly ($P < 0.01$) lower values at the outlet. The coefficient of variance (CV) of the time series data for all four parameters indicated a smaller temporal variability of water quality at the outlet compared to the inlet. As a result, the TGR operated as a mixer, making water quality less variable. It should be noted that the mixing effect significantly decreased NH₃-N content, which has a positive effect on TGR water. The effect can be compared with results from Chai et al. (2009) who reported a decreased total P concentration with an increased dissolved inorganic N, soluble reactive phosphorus, and total N, which was probably related to associative sediment processes (Wang et al. 2010a, b). This result is also in accordance with previous studies reporting that NH₃-N concentrations decreased as a result of the impoundment of reservoir flow (Morris and Fan 1998; Stow et al. 2001; Stanley and Doyle 2002). Nevertheless, markedly greater pH and COD_{Mn} levels and lower DO levels at the TGR outlet (relative to the inlet) may be due to a decreased water self-purification capacity and prolonged hydraulic residence time, resulting from a reduced rate in river flow (Morris and Fan 1998; Wei et al. 2009). Similarly, Macleod and Whitfield (1996) previously reported that a dam can have a considerable impact on water quality. In Turkey, Kurunc et al. (2006) also concluded that water quality characteristics were highly influenced by the presence of dams. In Brazil, Braniamarte et al. (2008) found that water pH in the Mogi-Guaçu River increased after damming. Their results were consistent with this study's pH observation; however, NH₃-N concentrations in river water found in their study remained relatively constant except for a peak value in November in the second year after damming, which was attributable to the simultaneous flooding event when the turbidity (suspended sediment) was also high. The similar and consistent results reached by these studies confirm observations found in this study.

However, reservoir water quality may not necessarily be altered by damming. In fact, water quality change in rivers after damming is affected by multiple factors, including source types and load of pollution, climate conditions, water storage capacity, management practices, etc. Even for rivers where no dam is present, differences in upstream and downstream water quality was observed. This was due to the emissions of a variety of point and non-point pollution from tributary catchments (Karakaya and Evrendilek 2010). Some studies have suggested that non-point pollution was the primary cause of water quality deterioration in the TGR (Zhang et al. 2005; Tian et al. 2010). In addition, other studies have shown that nutrient release from decaying plants can also deteriorate water quality, such as changing water pH levels (Howard-Williams and Howard-Williams 1978; Gaudet and Muthuri 1981). Besides plants, laboratory simulation experiments have revealed that WLF zone soils are a source of TGR water pollution (Liu et al. 2004; Yang 2004). Consequently, nutrient release from plants and soils in WLF zones is also believed to contribute to water quality deterioration. In general, TGR water quality deterioration was the result of the integrative effect of various mixed pollution sources as well as changing hydrological conditions. In order to protect Yangtze River water quality, tempo-spatial distribution of point and non-point pollution sources and their input into the TGR must be identified.

3.2 Temporal Trends in Water Quality Parameters

Temporal variations in inlet and outlet pH from 2006 to 2011 are illustrated in Fig. 2a. Inlet and outlet pH levels exhibited similar trends throughout the majority of the study period. Outlet water pH was stable, varying between 7.20 and 8.72, while inlet water pH showed significant variation, ranging from 6.64 to 8.59. Moreover, outlet water pH was higher than inlet water pH, exceeding 8.0 the majority of the time. The highest outlet value (8.72) was detected in October 2011 (during impoundment). Since 8.7 is the upper water pH limit for fish health (Water Quality Criteria 1963), this phenomenon may substantiate certain adverse impacts that TGR damming has on water quality. If conditions worsen, that is, if pH levels exceed 9, the release of P from lake sediment and the solubilization of heavy metals, ammonia, and salts would make conditions virtually impossible for aquatic life (Kelly 2009). Since an increase in pH could result from plant decay in water (Howard-Williams and Howard-Williams 1978; Gaudet and Muthuri 1981), WLF zone plants may be a pollution source in line with the highest outlet water pH observed since TGR impoundment.

As shown in Fig. 2b, DO exhibited similar seasonal variation between 2006 and 2011 at both the TGR outlet and inlet. The minimum outlet DO concentration (5.96 mg/l) in water was measured in October 2010 when TGR water levels exceeded 170 m. It should be noted that inlet water DO was higher than outlet water DO from November 2010 to April 2011, a period when the TGR maintained a high water level and WLF zone soils and plants were mostly submerged (Fig. 3). It is evidenced by a number of studies, that the decomposition of organic matter in the form of submerged plants and soils consumes a large amount of water DO. Moreover, Shuhaimi-Othman et al. (2007) found the lowest DO during flood months in Chini Lake and Branmart et al. (2008) observed a decreased trend in DO concentrations within the central reservoir of the Mogi-Guaçu River upstream and downstream of the dam. It is therefore evident that the construction of the Three Gorges Dam on the Yangtze River could decrease DO concentrations in TGR water due to the large-scale impoundment that resulted from damming.

COD_{Mn} concentrations in water exhibited similar temporal variations at both the outlet and the inlet (Fig. 2c). For the majority of the time, COD_{Mn} concentrations were higher at the outlet compared to the inlet. Peak concentrations of COD_{Mn} at the outlet occurred in the months of July and August, with a maximum value of 4.6 mg/L detected in August 2009 when TGR water

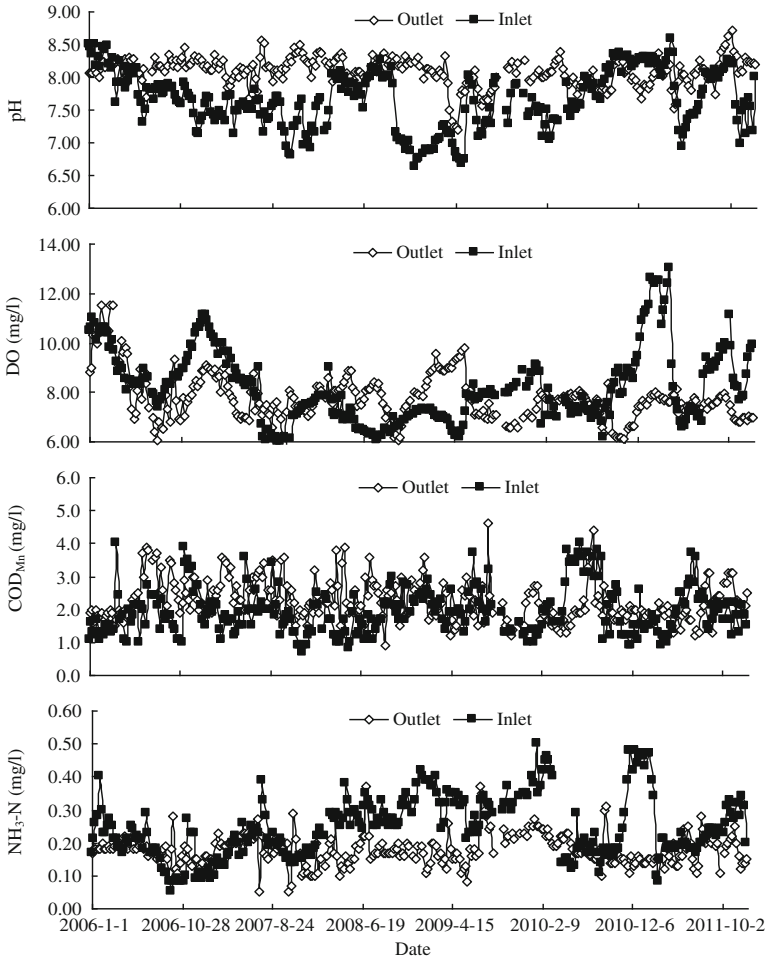


Fig. 2 pH, DO, COD_{Mn} , and $\text{NH}_3\text{-N}$ time series of Three Gorgers Reservoir from 2006 to 2011

levels were very low. Similarly, Mustapha (2008) recorded the highest COD_{Mn} concentration during the wet season in the Oyun Reservoir. As July and August rain fall under the rainy season in the TGR, low water levels were maintained during these months for flood control.

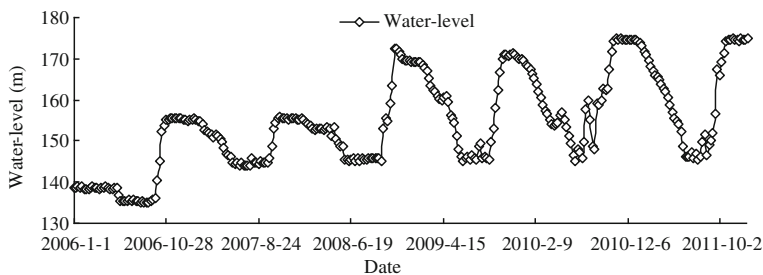


Fig. 3 Water level fluctuation in Three Gorgers Reservoir from 2006 to 2011

This anti-season operation put into practice to maintain the safety of the downstream region accounted for the highest COD_{Mn} concentration in TGR outflow (devoid of dilution) for the highly polluted discharge during the rainy season. It confirms the negative effects that dams have on river water quality.

Temporal $\text{NH}_3\text{-N}$ variation in the inlet and outlet are provided in Fig. 2d. Before October 2007, $\text{NH}_3\text{-N}$ trends in the inlet and outlet were similar when observed over time. However, differences between the inlet and outlet became greater after October 2007. It should be noted that $\text{NH}_3\text{-N}$ water concentrations were much higher at the inlet compared to the outlet between October 2010 and March 2011. Nevertheless, this high $\text{NH}_3\text{-N}$ input concentration did not significantly raise outlet water $\text{NH}_3\text{-N}$ content during the latter period, possibly due to a reduction by sediment associative processes after impounding (Wang et al. 2010b). Another explanation of this phenomenon may be that TGR inundation resulted in various sources being mixed in inlet water, leading to a decrease in $\text{NH}_3\text{-N}$ content by dilution or NH_3 gas discharge. Because the dam was built on a river-shaped reservoir, TGR water still flows a considerable distance through a long watercourse, which could lead to a decrease in $\text{NH}_3\text{-N}$ pollutant concentrations in outlet water. The implication is that TGR water quality can be improved by increasing the water flow rate during times when water pollution becomes critical.

3.3 Water Level Fluctuation and Estimation of Internal Pollution

Hundreds of river branches, including the Jialing and Wujiang rivers, also contributed to internal pollution loading. In addition, the submerged WLF zone could serve as a potential nutrient source, releasing nutrients from plants and soils under the water surface. Figure 3 shows the temporal variation in TGR water levels after 2006. In November 2008, TGR water levels exceeded 170 m, reaching a height of 172.6 m for the first time in recorded history. During 13 weeks in 2010, water levels exceeding 174 m were maintained for generating power and shipping. The highest water level (174.91 m) was reached in November 2010, and the lowest (135.07 m) in August 2006. Taking this into account, the largest amplitude during the study period was 39.84 m. A low water level is maintained in the TGR during summer to control flooding and a high water level is maintained in winter for purposes of generating power and shipping. The design minimum water level (145 m) had been maintained since 2007 while the design maximum water level is 175 m under normal operating conditions. Consequently, WLF amplitude of the TGR was designed to be 30 m. This value far exceeds other natural lake fluctuations, such as 1.27 m reported by White et al. (2008). Accordingly, the TGR has the largest WLF zone in the world. Inundation affects a large area, swallowing up farmlands where crops grew and large amounts of fertilizers were applied. The long period of low water level conditions during summer allows adequate time for plants to grow within the WLF zone. Plant biomass reaches maximum in the WLF zone or is harvested when the TGR starts to store water in October. Other researchers, like McLachlan (1971), had realized the serious consequence of plant nutrient release after a lake flooding event. Gaudet and Muthuri (1981) reported that N concentrations reached their maximum each year in September in Lake Naivasha due to the submergence of a large area containing a large amount of plants and soils. Chang and Wen (1997) found that nutrient release by biomass decomposition was the primary reason that caused rising nutrient concentrations during the first stages of reservoir construction in Taiwan. Taking this into account, nutrient release from plants and soils within the WLF zone could be an important factor contributing to the deterioration of TGR water quality. Thus, plant and soil management within the WLF zone is an important issue that governments and stakeholders must bear in mind.

Coefficients of Pearson's correlation analysis between water levels during flooding periods and water quality parameters are provided in Table 2. All WQIs are negatively related to water level, with pH and $\text{NH}_3\text{-N}$ at a significance level of 0.05 and DO and COD_{Mn} at a significance level of 0.01. With the exception of pH, correlation analysis confirmed the findings based on the time series data of the four parameters. A peak pH value was found when the TGR started storing water due to the rapid nutrient released from plants and soils during the early days of dam construction (Howard-Williams and Howard-Williams 1978; Gaudet and Muthuri 1981). Provided that TGR water quality is maintained at high levels for a period of 5 months and a large volume of water (with a lower pH, Fig. 2) flows into the TGR from upstream, the dilution effect of inflow water would lead to a decrease in pH. A negative correlation between pH and yearly amplitude in lakes was reported by White et al. (2008). They concluded that the relationship between water quality and WLF was area specific. For WLF systems induced by anthropogenic activity (such as dam operations), this artificial system would greatly affect water quality, considering its much greater fluctuation amplitude compared to natural WLF systems. Despite the well-established knowledge that DO concentrations have a negative relationship with temperature, the high and stagnant water level of the TGR might counteract occurrences of high DO levels during colder months.

In order to identify whether or not TGR impoundment worsened water quality as a result of the internal release of pollutants, water quality change was examined from the beginning to the end of impoundment (the threshold water level of impoundment being 165 m under normal climate conditions). For each impoundment period of each year, the total amount of DO, COD_{Mn} , and $\text{NH}_3\text{-N}$ internal release was calculated using Eq. 1 and Eq. 2. Results showed that impoundment time from 2008 to 2011 was associated with a decrease in DO and $\text{NH}_3\text{-N}$ and an increase in COD_{Mn} (Table 3). The mean decrease in DO was $1495.5 (\pm 1482.0) \times 10^3$ tons/yr and the mean increase in COD_{Mn} was $564.0 (\pm 405.0) \times 10^3$ tons/yr. For $\text{NH}_3\text{-N}$, each impoundment operation led to a mean decrease of $134.7 (\pm 86.1) \times 10^3$ tons/yr, likely due to the sedimentation (Wang et al. 2010b) and nitrification processes. It is noted that the amount of internal release varied dramatically from year to year. For instance, TGR impoundment led to a low DO consumption of 52.3×10^3 tons in 2008 and a high DO consumption of 3089.9×10^3 tons in 2011. This can be partially explained by the fact that the internal condition of the TGR was different year to year with regards to climate conditions, plant biomass, number of ships and tourists, etc. In addition, different impoundment times (lasting 7 weeks in 2008 and 17 weeks in 2011) may be another factor for differing measurements. It was assumed that the equilibrium of organic matter decomposition in the submerged WFL zone

Table 2 Pearson's correlation matrix for water-level, pH, DO, COD, and $\text{NH}_3\text{-N}$ of outlet water in Three Gorges Reservoir from 2006 to 2011

	Water-level	pH	DO	COD	$\text{NH}_3\text{-N}$
Water-level	1				
pH	-0.046*	1			
DO	-0.233**	-0.092	1		
COD	-0.197**	0.106	-0.084	1	
$\text{NH}_3\text{-N}$	-0.136*	-0.160**	-0.034	0.022	1

*Correlation is significant at the 0.05 level (2-tailed)

**Correlation is significant at the 0.01 level (2-tailed)

Table 3 Estimation of amount of contaminants by internal release in the Three Gorges Reservoir

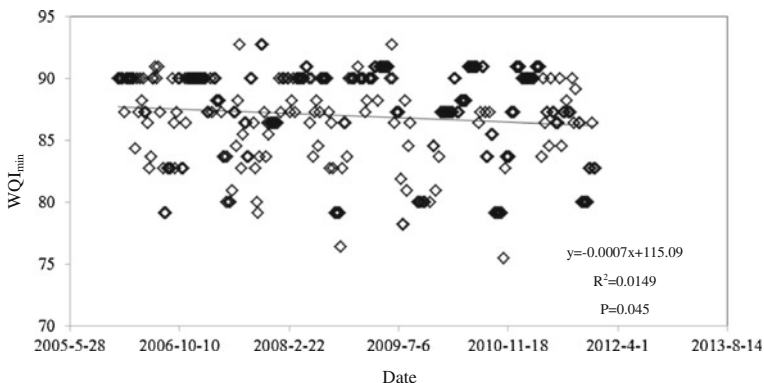
E_T	DO (10^3T)	COD _{Min} (10^3T)	NH ₃ -N (10^3T)	Flooding periods (Week)
2008	-52.27	467.37	-257.61	20
2009	-431.70	390.93	-71.82	12
2010	-2408.32	242.56	-130.81	29
2011	-3089.87	1155.15	-78.55	30
Mean	-1495.54 (± 1482.01)	564.00 (± 405.0)	-134.70 (± 86.1)	23

Plus values mean net release and minus values mean net storage

can be obtained after a longer duration of impoundment. On the other hand, the first impoundment of the TGR in 2008 released 467.37×10^3 tons of COD_{Min}, which was the second largest amount investigated in this study. It is possible that the initial impoundment led to a large quantity of nutrient release from the pre-existing farmlands within the WFL zone where soils likely contain high levels of nutrients and other pollutants as a result of centuries of crop cultivation. COD_{Min} release dynamics were associated with the relatively high weekly DO depletion observed in 2008 (Fig. 2b). Multiple laboratory simulation experiments have indicated that TGR impoundment can cause water deterioration due to the submersion of plants and soils in the WLF zone (Liu et al. 2004; Yang 2004). Furthermore, the ships and tourists that pass through the TGR and subsequently cause pollutants were also an important factor that influenced the amount of internal pollutant release. It can be concluded that impoundment posed adverse effects on TGR water quality in the form of large DO consumption and internal COD_{Min} release, being affected by impoundment duration, WFL zone vegetation coverage, shipping and tourism, etc.

3.4 Water Quality Assessment Using Indexing Method

WQI is an integrative indicator used to assess water quality changes based on multiple measured parameters. TGR outlet WQI_{min} was calculated to assess the effects of dam construction on Yangtze River water quality. Linear fitting was employed to determine whether or not a significant long-term trend in water quality change was present at the TGR outlet. Results (Fig. 4.) showed that the average, maximum, and minimum value of WQI_{min} was 87.0, 92.7,

**Fig. 4** Linear fitting for minimum water quality index in TGR outlet water from 2006 to 2011

and 75.5, respectively, and TGR water could be categorized to be in good condition for the majority of time from 2006 to 2011, after dam completion. Moreover, this finding was consistent with the evaluation by the Environmental Quality Standards for Surface Water of China. Although scientists and environmentalists worried that TGR water deterioration was worse than anticipated (Stone 2011), results from this study showed that water quality in the main channel of the Yangtze River remained generally good. Furthermore, linear regression showed significant decreasing trends in TGR outlet water quality through the whole study period ($P=0.045$). Although the slope was infinitesimal (-0.0007), the negative value indicated that TGR water deterioration could become more serious in the future. If there are no proper and effective measures to reduce pollutants around the TGR and upstream of the Yangtze River, the safety of TGR water quality will be more at risk for China's sustainable development. In fact, the Chinese government has focused on the ecological and environmental protection of the TGR in recent years. Many mitigation measures, such as banning farming within the WLF zone, reducing non-point source pollution above the WLF zone, treating sewage in riparian townships and ship traffic, implementing riparian buffers, etc., have been proposed in practice (Chang et al. 2010). To better achieve the goal of improving water quality, stricter management strategies to reduce waste water emissions in the entire reservoir region should be taken to prevent water quality degradation (Lehmann and Rode 2001).

Preliminary results from this study indicated that the construction of the Three Gorges Dam deteriorated water quality. This conclusion was based on a reduction in flow velocity, anti-season dam regulation, decomposition or the release of pollutants from plants and soils in the WLF zone, and various contaminant loads derived from agriculture (above the WLF zone), industry, and shipping. Some studies have pointed out that non-point pollution was a dominant factor that contributed to the deterioration in TGR water quality (Zhang et al. 2005; Tian et al. 2010); however, reliable measurements of TGR non-point pollution loads remain scarce (Tullos 2009). Therefore, well-designed monitoring programs are required to identify spatial distribution of point and non-point pollution sources while quantifying their loads into water bodies in support of the optimization of TGR environmental management.

4 Conclusions

The present study found that TGR outlet water (Yichang) contained higher pH and COD_{Mn} levels and lower DO and $\text{NH}_3\text{-N}$ levels compared to TGR inlet water. The anti-season operation of the reservoir's water levels (between 145 and 175 m above mean sea level) created the world's largest WLF zone, for which the anaerobic submerged land area, including plants and soils, is subjected to underwater decomposition processes. Internal release from submerged plants and soils in the WLF zone as well as tributary watersheds, shipping, and tourism appears to be a significant TGR pollution source. TGR budget water balance analysis of DO, COD_{Mn} , and $\text{NH}_3\text{-N}$ between the outlet and inlet showed that reservoir impoundment led to an increase in COD_{Mn} and a decrease in DO. Water quality assessment based on WQI_{min} suggested that TGR water quality remained in good condition; however, linear regression showed that water quality could significantly decline in the future. This implies that more effective pollution mitigation strategies should be taken to improve water quality in the TGR. Further studies should also be carried out to determine the spatial distribution of point and non-point pollution sources and to ascertain the major factors that govern TGR water quality change. A greater number of water quality parameters and longer time series datasets are also needed to further evaluate TGR water quality change after dam completion.

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