Water quality assessment of an urban river receiving tail water using the single-factor index and principal component analysis

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ABSTRACT

Tail water from wastewater treatment plants (WWTP) serves as a major supplementary water source for scenic water bodies, whose water quality is one of the major focuses of public and scientific inquiries. This study investigated the temporal and spatial variations in water quality of Tangxihe River, a eutrophic urban river receiving tail water from a nearby WWTP in Hefei City, using the single-factor index (SFI) and principal component analysis (PCA). The results of SFI indicated that the most important parameters responsible for low water quality were total nitrogen (TN) and ammonia (NH_4^+-N). PCA showed that tail water from the WWTP greatly reduced water quality, as demonstrated by the significantly increased SFIs and integrated principal component values (F values) of the sampling points around the drain outlet of the WWTP (T_3, T_4 and T_5). The sampling points located at the upstream of the river (T_1) and up the water-gate of Chaohu Lake (T_6) had negative F values, indicating relatively higher water quality. In addition, the season had a significant effect on the water quality of the river. Moreover, we discuss measures to improve the water quality of urban rivers in order to maintain their ecological functions.

Key words | principal component analysis, single-factor index, tail water, urban river, water quality assessment

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INTRODUCTION

Urban rivers play a significant ecological, economic, and social role in the sustainability of human society. However, rapid urbanization and the consequent increase of water demand and wastewater discharge have caused severe water shortages and pollution in nearby rivers. In a number of water-scarce cities in China, effluent from wastewater treatment plants (WWTP) has become a primary supplementary water source for scenic rivers (Lyu et al. 2016). Unfortunately, given the relatively low discharge standard of pollutants for WWTP (Table S1, see Supplementary Material, available with the online version of this paper), the effluent likely becomes a pollution source for these rivers. Thus, changes in the water quality of these rivers increasingly cause great concern among the public and scientific researchers.

The availability of suitable tools to evaluate water quality is essential for successful risk assessment and management of urban rivers, and considerable effort has been made in the development of comprehensive water quality assessment methods (Wang et al. 2017a). Several methods have been developed to assess water quality, including the methods of single-factor index (SFI), biological indices (Pham 2017), comprehensive pollution index (Effendi 2016), the Nemerow pollution index (Chen et al. 2016), principal component analysis (PCA) (Ali & Khairy 2016), and comprehensive water quality identification index (Wang et al. 2017b). The SFI method, based on the *Environmental Quality Standards for Surface Water* (GB3838-2002) (EPA of China 2002), can be used to directly understand the

relationship between water quality status and the assessment standard and identify the main factors leading to water pollution. The PCA method, which interprets the whole data set, provides data reduction and summarizes the statistical correlation among water quality constituents with minimum loss of the original information (Ouyang *et al.* 2006; Zhang *et al.* 2014).

Using the SFI and PCA methods, the objectives of this study are to assess the seasonal variation of the water quality of an urban river that receives the discharge of a WWTP, identify the main indicators responsible for the pollution condition of the river and reveal the main polluted area.

MATERIALS AND METHODS

Study site and sampling points

Tangxihe River, as a tributary of Chaohu Lake and an important landscape river in Hefei City, has a basin area of 50 km². It originates from Nanyan Lake, with a depth of less than 3 metres. To investigate the temporal variation in water

quality of the river, we selected six points (T_1, T_2, T_3, T_4, T_5 and T_6) along the river as water sampling sites (Figure 1). Due to insufficient headwater flow, the effluent of a nearby domestic WWTP (Tangxihe WWTP) is discharged into Tangxihe River as a major supplementary water source at the site between T_3 and T_4 at a flow rate of 30,000 m³/d. The water quality parameters of the effluent from spring of 2015 to summer of 2016 are shown in Table S1 (see in Supplementary Material, available with the online version of this paper).

Site T_1 is located at the upstream of Tangxihe River; Site T_2 is close to a residential area receiving nearby storm runoff; Site T_3 and Site T_4 are close to the point where the effluent from Tangxihe wastewater treatment plant is discharged into the river; Site T_5 is near Baohe Road and receives some road runoff; and Site T_6 is located at the downstream and before the water-gate of Chaohu Lake.

Water sampling and analysis

The water samples were collected from the six sites every month from March 2014 to February 2016. The physico-chemical parameters, including pH, dissolved oxygen
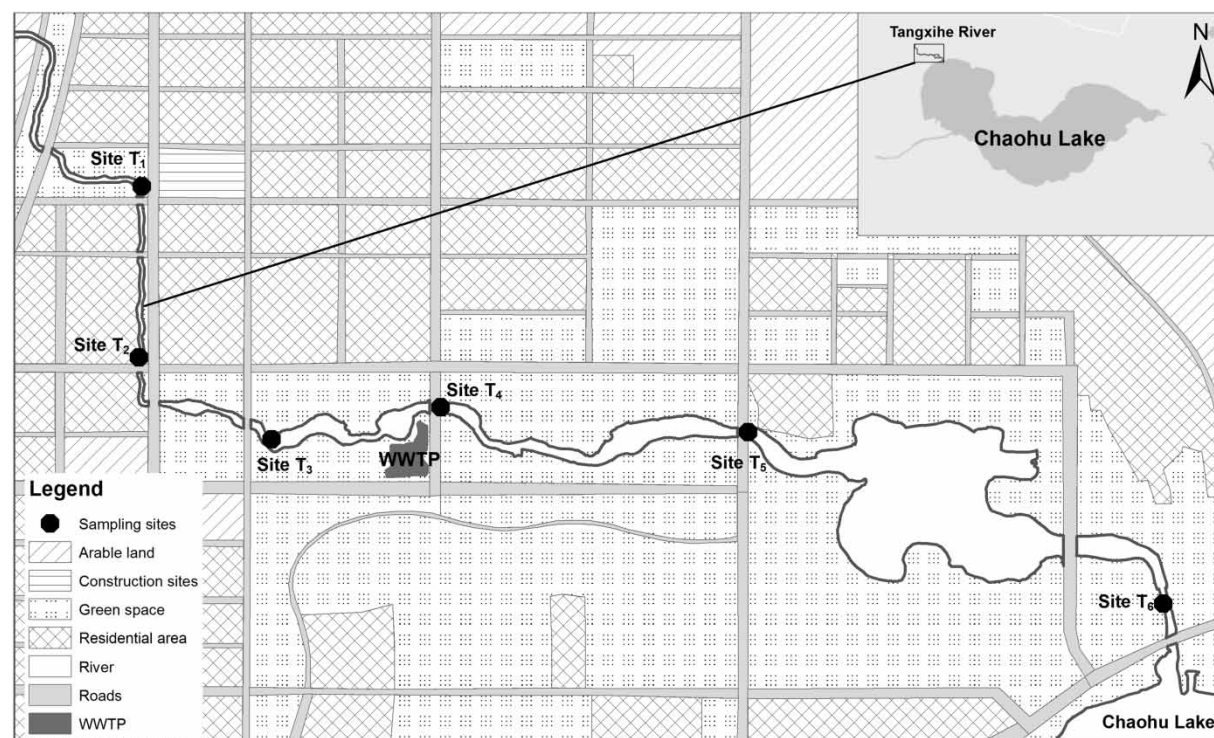

Figure 1 │ Sampling sites of Tangxihe River.

(DO), total suspended solids (TSS), and turbidity were monitored *in situ* with a portable water quality analyser (Professional Plus, YSI, USA), portable turbidimeter (2100Q, HACH, USA) and TSS portable instrument (HACH, CO, USA). Water samples were taken to the laboratory and analysed as soon as possible thereafter. The total nitrogen (TN), ammonia (NH_4^+-N), nitrite (NO_2^--N), nitrate (NO_3^--N), total phosphorus (TP), inorganic phosphorus (PO_4^{3-}-P) and chemical oxygen demand (COD) were determined using the methods proposed in *Standard Methods for Water and Wastewater Monitoring and Analysis*.

Water quality assessment methods

Single-factor index method

To evaluate the water quality of Tangxihe River with the integration of a regulatory standard, the SFI method was used to compare the selected parameters (COD, TN, TP, NH_4^+-N and DO) with the threshold concentrations in *Environmental Quality Standard for Surface Water* (GB3838-2002) ([EPA of China 2002](#)). The threshold values of five grades of the standard are listed in Table S2 (see in Supplementary Material, available with the online version of this paper). The water quality standard for Tangxihe River is Grade V, so we selected Grade V as the target standard with which the determined parameters were compared. The SFI was calculated by Equation (1):

$$P_i = \frac{C_i}{C_{ti}} \tag{1}$$

where P_i represents the SFI value of water quality of indicator i, C_i (mg/L) represents the measured value of indicator i, and C_{ti} (mg/L) represents the threshold value of Grade V for indicator i under *Environmental Quality Standard for Surface Water*. Since DO values generally vary in an opposite direction to the other indicators (higher DO values indicate higher water quality), DO concentrations need to be transformed into their inverses before the SFI calculation.

Principal component analysis method

To combine the multiple indicators into an independent comprehensive index to represent the original data, an assessment method based on PCA was used. First, due to their different dimensions, all original indicators need to be standardized using the following formula:

$$C_s = \frac{(C_0 - C_m)}{STD} \tag{2}$$

where C_s is the standardized value of the indicator, C_0 (mg/L) is the original value of the indicator, C_m (mg/L) is the mean value of the original indicators, and STD is the standard deviation of all original values of the indicators.

Then, a Pearson correlations matrix was prepared within the standardized indicators using SPSS 17.0 (SPSS Inc., Chicago, USA). According to the cumulative contribution of variance and the eigenvalue of the correlations matrix, the principal components (P_1, P_2, $P_3 \ldots P_i$) can be extracted, with a cumulative contribution of variance more than 65% and eigenvalue more than 1. The coefficient between the principal component P_i and each standardized indicator (*Cof*) was obtained from the component score coefficient matrix, and then the F value of the principal component P_i was calculated by Equation (3):

$$F_i = \sum_{j=1}^{n} C_j \times Cof_{ij} \tag{3}$$

where F_i is the F value of the principal component P_i, n is the number of standardized indicators, C_j is the value of standardized indicator j, and Cof_{ij} is the coefficient between the principal component P_i and standardized indicator j.

Finally, the F is calculated as follows:

$$F = \sum_{i=1}^{n} \lambda_i \times F_i \tag{4}$$

where F is the integrated F value of all standardized indicators, λ_i is the eigenvalue percentage of principal component i of the total eigenvalues of all extracted principal components.

Statistical analysis

The average SFI and F values of each season were calculated. Two-way analysis of variance (ANOVA) was used to

test the differences in SFIs and F values between different sampling sites and seasons using SPSS 17.0 (SPSS Inc., Chicago, USA). The post hoc tests that compare the differences among sampling sites and seasons were conducted using the Student–Newman–Keuls method. Homogeneity of variances was ensured with a Levene's test before the ANOVA tests were performed. All significances are reported at the $P < 0.05$ level, unless otherwise stated.

RESULTS AND DISCUSSION

Water quality assessment using SFI method

SFI represents the relative pollution status compared with the target water quality standard. The SFI values of COD, TN, TP, NH_4^+-N and DO of the six sampling sites in different seasons are shown in Figure 2.

Except for DO, the SFI of all indicators showed significant differences among the sampling sites ($P < 0.01$, Table 1), and T_3, T_4 and T_5 (4.12, 4.52 and 3.99, respectively) generally had higher SFIs than T_1, T_2 and T_6 (2.22, 3.07 and 2.43, respectively). For TP and NH_4^+-N, the SFIs followed a similar trend to TN. However, the post hoc test of COD among the sampling sites demonstrated the mean SFI of COD at T_6 was comparable to that at T_3, T_4 and T_5. Given that the effluent from the WWTP joins the river at the location between T_3 and T_4, we can interpret that the tail water considerably impacted the river's water quality.

The effect of season on the water quality of the river was demonstrated by the results of two-way ANOVA (Table 1). The SFI of TN significantly differed among seasons ($P < 0.01$), with the lowest mean value of 1.95 ± 1.28 in fall, and highest mean value of 4.03 ± 1.43 and 4.83 ± 3.27 in spring and winter, respectively. With respect to TP, season also had a notable effect on its SFIs, showing the lowest value of 0.46 ± 0.44 in fall and similar levels in other seasons. The SFI of NH_4^+-N reached its highest level in winter, with the value of 2.39 ± 1.41. For other indicators, including COD and DO, the differences in their SFIs among different seasons were not significant ($P > 0.05$).

The SFI values, which represent the gap between the water quality standard thresholds and the real water quality,

had distinct ranges for different indicators. The SFI of TN and NH_4^+-N, with the mean values of 3.39 ± 2.41 and 1.76 ± 1.45, were notably higher than that of TP (0.86 ± 0.65), COD (0.65 ± 0.40) and DO (0.65 ± 0.54). The significant difference among indicators implies that TN and NH_4^+-N were the main factors responsible for the low real water quality compared with the target water quality.

Nitrogen and phosphorus pollutants primarily come from industrial wastewater (untreated or without thorough treatment), domestic wastewater, organic waste, livestock or poultry droppings, agricultural fertilizer, etc. At the location of sampling points T_3 and T_4 (close to a sewage treatment plant discharging industrial wastewater) and T_5 (near the Baohe Road, which receives road runoff), the concentration of NH_4^+-N and P showed a dramatic elevated trend.

Furthermore, the higher SFI values of all indicators indicate that the pollution condition of the river was worse in spring and winter than in fall. Apart from the seasonal pattern of tail water from the WWTP, the possible factors driving this seasonal variation include the following. (1) The increased algae biomass in fall. For TN, for example, Wang *et al.* (2011) found that in the growing process of algae, the nutrient concentration gradient between the pore water and overlying water increased, with the absorption of a large amount of nutrients. This promoted the release of nutrients from the pore water to overlying water and ultimately led to the increase in concentration of TN during the winter period. (2) Hydrological force and water temperature. The river's inflow water quantity in the flood and non-flood seasons, along with its temperature, are both important factors influencing water quality (Rothenberger *et al.* 2014). In the summer and fall, the increased rainfall and temperature not only dilutes the pollutants but also promotes their degradation by microorganisms. (3) The composition of both phytoplankton and zooplankton. Ye *et al.* (2006) showed that the NH_4^+-N concentration exceeded the target threshold significantly in the summer, possibly due to the release of NH_4^+-N from sediment and the role played by microbes. In addition, it showed that one possible cause for high TP levels was the release of phosphorus absorbed by Fe from sediment into the overlying water during the summer (Ingall & Jahnke 1994).
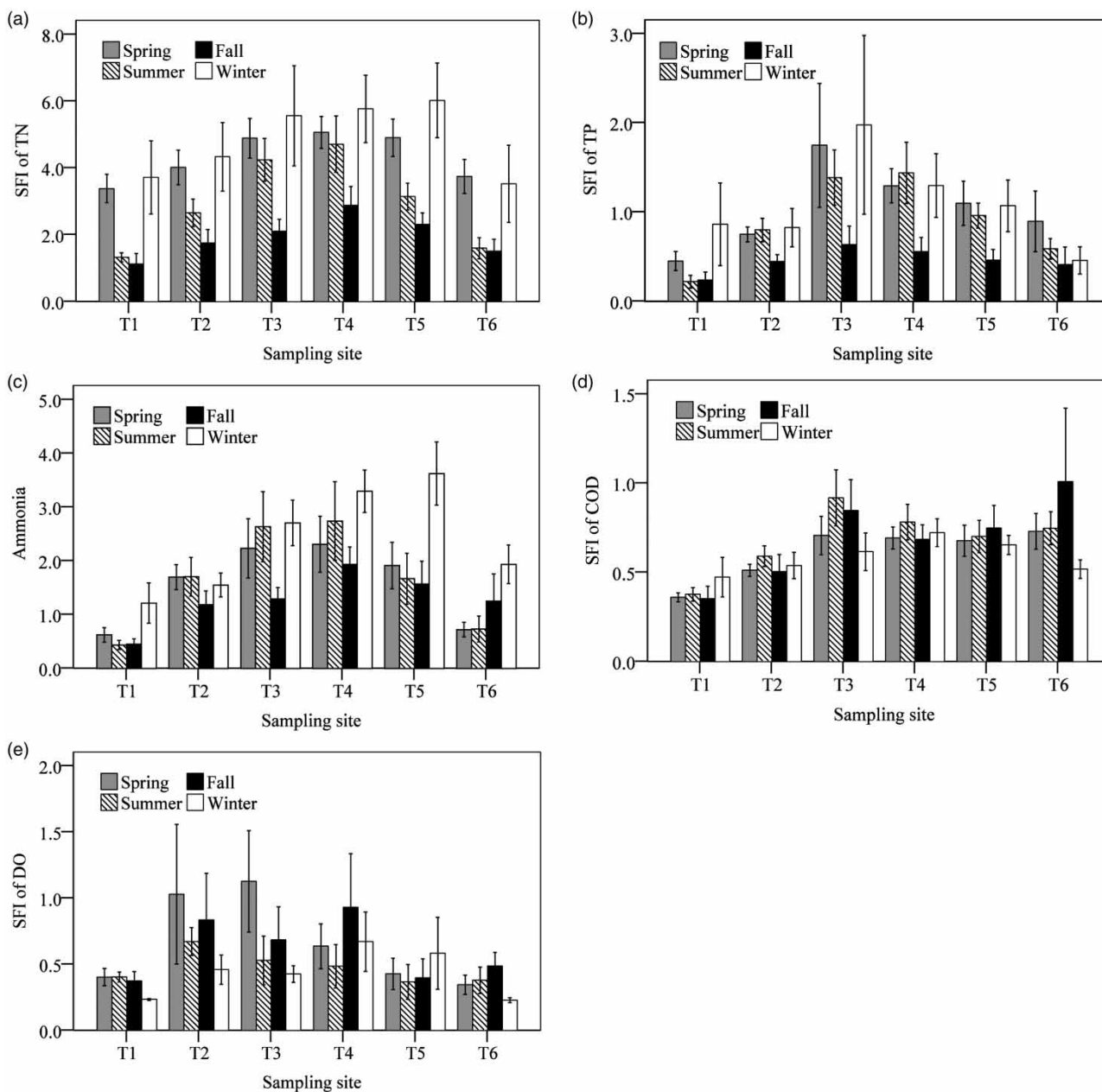
Figure 2 | Single factor indices (SFI) of (a) total nitrogen (TN), (b) total phosphorus (TP), (c) ammonia (NH_4^+-N), (d) chemical oxygen demand (COD), and (e) dissolved oxygen (DO) of the six sampling sites in different seasons.

Water quality assessment using PCA method

The value of F reflects the comprehensive pollution state of different sampling points, with a higher F value signifying lower water quality. The values of F at different sampling points in different seasons are shown in Figure 3.

Since a higher F value represents lower water quality, and based on the classification of pollution degree, the water quality of the sampling points T_3, T_4 and T_5 always showed a serious pollution situation in spring, summer and winter, while the conditions of T_1 and T_6 were less severe. A possible reason for this observed variation is that the WWTP effluent enters the river near the location

Table 1 | Result of two-way ANOVA for the single factor index (SFI) of total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD), ammonia (NH_4^+-N), dissolved oxygen (DO) and F value in Tangxihe River with the sampling sites and seasons as the two factors

Indicator	Site		Season		Site × Season	
	F	Sig.	F	Sig.	F	Sig.
SFI of TN	6.65	0.00	18.323	0.00	0.408	0.975
SFI of TP	6.484	0.00	5.038	0.002	0.602	0.871
SFI of NH_4^+-N	12.64	0.00	7.184	0.00	1.12	0.342
SFI of COD	4.734	0.00	1.753	0.158	0.61	0.864
SFI of DO	1.78	0.12	0.644	0.588	0.878	0.59
Factor (F)	11.673	0.00	19.744	0.00	0.709	0.773

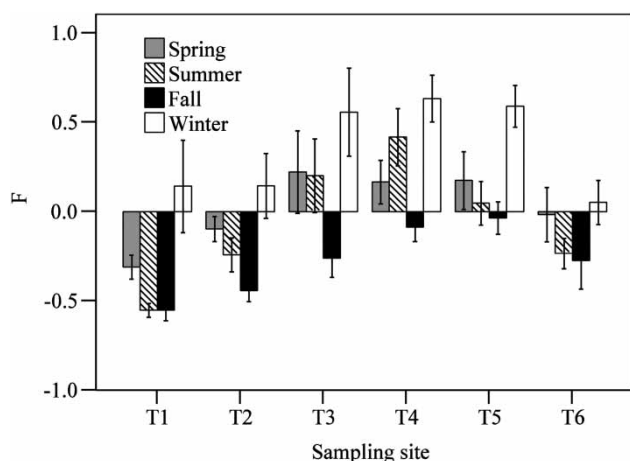*Sig.* represents the significance level.

Figure 3 | The integrated value of principal component analysis (F) of different sampling points in different seasons.

between T_3 and T_4, eventually leading to the serious pollution situation, which is consistent with the result of the SFI analysis. Furthermore, the location of T_1, has good water quality readings. Since T_2 was closer to a residential area, and T_5 receives drainage from the road, these points could easily be influenced by human activities and storm pollution, which are considered to be the main sources of NH_4^+-N (Ikem *et al.* 2013). With respect to T_6, one possible reason for its changes in water quality over time may be the occurrence of an algae bloom. Overall, the specific results of the sampling points T_3, T_4 and T_5 may be related to their location near the WWTP, results that are supported by Olsen *et al.* (2012).

In addition, the F values were negative in fall while keeping the highest value in winter of all sampling points

(seen in Figure 3), indicating the water quality of all sampling points was in good status in fall while seriously polluted in winter. It means the F value changes showed a significant seasonal pattern (similar to SFIs, seen in Table 1, $P < 0.01$), which is consistent with the study by Sharma & Chhipa (2016). The mean F of each season corresponded to the following order: fall (-0.27 ± 0.34) < spring (-0.029 ± 0.46) = summer (-0.02 ± 0.50) < winter (0.35 ± 0.55). The observed high water quality in fall and low water quality in winter may be due to rainfall (average 65.00 mm in fall and 39.33 mm in winter) and water temperature (average 22°C in fall and 8.33°C in winter), which is supported by Helena *et al.* (2000).

Based on the seasonal and spatial variations of water quality, the following measures to improve the water quality of Tangxihe River are proposed (including considerations of seasonality): (1) controlling the storm event runoff, which is the main source of NH_4^+-N and P; (2) improving the effluent standard for WWTPs, given the considerable pressure tail water exerts on river water quality; (3) implementing *in situ* approaches to restore vegetation and support the aquatic ecosystem, which is favourable for maintaining water quality (Wu *et al.* 2013). Regarding the species of vegetation to be restored, various studies have been conducted that stress the role of emergent and submerged plants, e.g., *Acorus calamus, Iris tectorum, Canna generalis* and *C. generalis*, in removing nitrogen and phosphorus pollutants and controlling algal bloom (Li 2011).

CONCLUSIONS

Water quality of the urban river receiving tail water as water source could be considerably impacted by the tail water quality. The main factors responsible for the pollution condition of Tangxihe River were TN and NH_4^+-N. The water quality was always the lowest at the sampling points close to the effluent outlet of the WWTP (T_3, T_4 and T_5), while those located at the upstream of the river (T_1) and before the water-gate of Chaohu Lake (T_6) were higher. Hence, to improve the water quality of the river, the supplementary water resource (water from WWWTP) should be controlled in its quality. Moreover, Tangxihe River was most polluted in winter and least polluted in fall. Therefore, the measure

of re-vegetating the surrounding area with hardy plants of strong repair ability should be taken to improve the Tangxihe River water quality.

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