Assessing water quality for urban tributaries of the Three Gorges Reservoir, China

Senlin Zhu, Abazar Mostafaei, Wenguang Luo, Benyou Jia and Jiangyu Dai

ABSTRACT

Water quality assessment is essential for water resources management. This paper presents a comprehensive evaluation of water quality conditions in three urban tributaries of the Three Gorges Reservoir, China. The Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) and Nemerow Pollution Index (NPI) approach were used in this study. Generally, the assessment results of the NPI approach are consistent with that of the CCME-WQI approach. However, the NPI method overemphasized the influence of the most serious pollutant factor, and thus this method should be used with caution for water resources managers. The CCME-WQI values indicated that the water quality conditions in the Wubu River were quite good during the period 2013–2015. Water quality conditions in the upstream sections of Yipin and Huaxi River are good. However, when the river drains through urban areas, water quality conditions greatly deteriorate due to the excessive release of household and municipal sewage, and industrial wastewater, especially for Huaxi River. Thus, waste water management becomes more and more imperative in urban regions of China. Meanwhile, assessment results indicate that the CCME-WQI approach can provide a reference for decision-makers on water resources management.

Key words | CCME-WQI, NPI, Three Gorges Reservoir, urban rivers, water quality

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INTRODUCTION

In China, the single factor pollution index (SFPI) method is the most commonly used approach to evaluate water quality conditions in surface water bodies (Yan *et al.* 2015). In the SFPI method, water quality indexes are normally categorized based on the Environmental Quality Standards for Surface Water in China (GB3838-2002), which was published by the Ministry of Environment Protection of China in 2002. The SFPI approach can easily provide water quality classification for the assessed water quality indexes. However, it uses the worst water quality classification of the assessed water quality indexes as the final water quality classification and gives biased results as a result (Ji *et al.* 2016). Except for the SFPI method, another approach that has been widely used to assess different surface water bodies in China is the Nemerow Pollution Index (NPI) approach. Detailed applications can be found in Liu *et al.* (2007) and Xu *et al.* (2010). In Canada, the Water Quality Guidelines Task group of the Canadian Council of Ministers of the Environment proposed a new water quality assessment approach in 2001 (Canadian Council of Ministers of Environment Water Quality Index, called CCME-WQI hereafter) (CCME 2001). The CCME-WQI approach provides a flexible index template, and allows researchers to select appropriate water quality objectives according to their own requirements (CCME 2001; Hurley *et al.* 2012). Due to the flexibility of the CCME-WQI approach, it has been applied

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to evaluate water quality conditions all over the world (Lumb *et al.* 2012; Damodhar & Reddy 2013; Zhao *et al.* 2016). Lumb *et al.* (2012) found that the CCME-WQI method is the most stringent one to grade water quality status for aquatic uses when compared with other assessment approaches. Damodhar & Reddy (2013) concluded that the CCME-WQI method is adequate for evaluating the impacts of industrial effluent on the river water bodies. Zhao *et al.* (2016) indicated that the CCME-WQI approach can be used to effectively evaluate whether the overall water quality conditions meet the specified water quality objectives. Moreover, the United Nations Environmental Program advised that the CCME-WQI method is a suitable tool for assessing the overall water quality conditions of drinking water globally (Rickwood & Carr 2009).

The Three Gorges Project has brought substantial social and economic benefits, such as flood control, hydro-power generation, and navigation. However, the Three Gorges Project has long-term impacts on the ecosystem of Yangtze River. For example, severe algae blooms have been reported in many tributary bays since the initial impoundment of the Three Gorges Reservoir (TGR) in 2003 (Ma *et al.* 2015). Water quality conditions in TGR have been frequently studied. Previous studies mainly focused on pollution sources and loading estimation (Shen *et al.* 2014; Zhang *et al.* 2016), and the temporal and spatial variation of the water quality parameters in some rural tributaries of the TGR, especially those that will be dramatically impacted by backwater from TGR, such as Xiangxi River and Da-Ning River (Hu *et al.* 2013). Some studies have focused on water quality variations within the main stem and large tributaries of the TGR over a relatively long time period (Zhao *et al.* 2013, 2016). However, few studies have focused on water quality variations within some urban tributaries in the upper TGR part, especially in the Chongqing section, since these urban tributaries play a significant role in the water pollution of TGR.

The main objective of the study is to apply the CCME-WQI approach to assess the water quality condition of three urban tributaries in the upper TGR from 2013 to 2015. The assessment results of the NPI method were used as a comparison. The results will aid in the optimization of water resources for sound environmental management.

MATERIALS AND METHODS

Study area

The Yangtze River is the largest river in China and the third largest in the world. The TGR is located at the end of the upper Yangtze River. It is one of the largest man-made reservoirs in the world with a surface area of 1,080 km^2, a storage capacity of 39.3 billion m^3, and a watershed area larger than 1 million km^2 (Huang *et al.* 2006). Since the normal impoundment in 2010, water levels varied between 145 and 175 m. The impounded area is more than 600 km long, more than 120 m deep in places, and forms a markedly dendritic drainage pattern (Holbach *et al.* 2015). The TGR watershed includes 21 counties with a total area of 58,000 km^2, including Chongqing and Yichang, with a population of 20.68 million. TGR water storage is mainly in the Chongqing area. Three urban tributaries, located in Chongqing City (Banan District), were studied in this paper. Data from eight monitoring stations in these three rivers were used in the water quality analysis (Table 1). Water quality data sets were in the period from 2013 to 2015, with one sampling per month.

Mathematical structure of NPI index

The NPI method is a water pollution index which takes extreme values into account using a weighted environmental quantity index. This index can be calculated by

Table 1 | Characteristics of the studied rivers

River	Length (km)	Watershed area (km^2)	Annual flow rate (m^3/s)	Monitoring stations
Yipin	51.0	363.0	5.28	3 (CSZ, BJDK, YHQ from upstream to downstream)
Huaxi	63.62	268.46	3.6	3 (NHCK, JLY, SLQ from upstream to downstream)
Wubu	84.4	871.0	13.11	2 (JQ, ZC from upstream to downstream)

three steps as follows: (1) identify the classification of each water quality parameter according to the national water quality standards, (2) determine the corresponding pollution index for each classification, and (3) determine the water quality classification by calculating the NPI value. The mathematical formula for the NPI index is as follows:

$$P = \sqrt{\frac{\left((1/n)\sum_{i=1}^{n} P_i\right)^2 + [(P_i)_{MAX}]}{2}} \tag{1}$$

where P is the NPI, n is the total number of water quality parameters, P_i is the pollution index of parameter i, $(P_i)_{MAX}$ is the maximum pollution index. P_i can be computed by the following formula:

$$P_i = \frac{C_i}{C_0} \tag{2}$$

For dissolved oxygen:

$$P_{DO} = \begin{cases} |C_{DOf} - C_i|/(C_{DOf} - C_0) & C_i \geq C_0 \\ 10 - 9C_i/C_0 & C_i < C_0 \end{cases} \tag{3}$$

where C_i is the measured value of parameter i, C_0 is the desired water quality standard value of parameter i. C_{DOf} is the saturated dissolved oxygen concentration, and it can be calculated with the formula employed in QUAL-2 K model (Chapra *et al.* 2012).

The NPI method divides water quality conditions into five classifications generally:

Class I: $P < 0.8$, and water is clean;
Class II: $0.8 \leq P < 2.5$, and water is slightly polluted;
Class III: $2.5 \leq P < 4.25$, and water is moderately polluted;
Class IV: $4.25 \leq P \leq 7.2$, and water is heavily polluted;
Class V: $P > 7.2$, and water is seriously polluted.

Mathematical structure of CCME-WQI approach

The CCME-WQI method is based on the following three elements: scope (F_1), frequency (F_2), and amplitude (F_3), which has been well documented in Lumb *et al.* (2006). A brief description is presented here.

F_1 (Scope)

Scope (F_1) is used to measure the number of water quality parameters that do not meet desired water quality objectives. It can be calculated by Equation (4):

$$F_1 = \frac{\text{Number of failed variables}}{\text{Total number of variables}} \times 100 \tag{4}$$

F_2 (Frequency)

Frequency (F_2) is used to measure how often a water quality objective is not met. It can be calculated by Equation (5):

$$F_2 = \frac{\text{Number of failed tests}}{\text{Total number of tests}} \times 100 \tag{5}$$

F_3 (Amplitude)

The amplitude (F_3) is used to represent the amount by which the failed test values do not meet their water quality objectives. Three steps are needed to calculate F_3, as detailed below.

First, the number of times by which an individual concentration is greater than or less than the water quality objective should be computed, which is also known as 'excursion'. If the test values exceed the water quality objective, excursion can be calculated by Equation (6):

$$\text{excursion}_i = \left(\frac{\text{Failed Test Value}_i}{\text{Objective}_i}\right) - 1 \tag{6}$$

For the cases when the test values fall below the water quality objective, excursion can be calculated by Equation (7):

$$\text{excursion}_i = \left(\frac{\text{Objective}_i}{\text{Failed Test Value}_i}\right) - 1 \tag{7}$$

Second, the total amount when the individual tests are out of compliance (*nse*) should be calculated. Normally, Equation (8) is used:

$$nse = \frac{\sum_{i=1}^{n} \text{excursion}_i}{\text{Total number of tests}} \tag{8}$$

The amplitude (F_3) is then calculated by an asymptotic function that scales the normalized sum of the excursions from objectives to yield a value between 0 and 100:

$$F_3 = \frac{nse}{0.01nse + 0.01} \tag{9}$$

Finally, the CCME-WQI index is calculated as is shown in Equation (10):

$$CCME - WQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right) \tag{10}$$

The above formulation generates a CCME-WQI value between 0 and 100. A CCME-WQI value closes to 0 represents very poor water quality conditions. A CCME-WQI value closes to 100 indicates excellent water quality conditions. The assessment results can be subdivided into the following five categories: Excellent: 95–100; Good: 80–95; Fair: 65–79; Marginal: 45–64; and Poor: 0–44.

To calculate the CCME-WQI value, the water quality parameters and objectives need to be specified initially. The monthly measured values for 25 water quality parameters in the period 2013–2015 were obtained from the Chongqing Environment Protection Bureau. Water quality parameters include: water temperature, pH, dissolved oxygen (DO), permanganate index (COD_{Mn}), 5-day biochemical oxygen demand (BOD_5), ammonia (NH_4), volatile phenol, cyanide, arsenic, mercury, chromium, lead, cadmium, petroleum, electrical conductivity, chemical oxygen demand (COD), total nitrogen (TN), copper, zinc, total phosphorus (TP), fluoride, fecal coliform, anionic surfactant, sulfide and selenium. Based on the field measurements of water quality relevant to the study site, nine parameters which pose a threat to the water quality of the TGR were selected as parameters for calculating the CCME-WQI. These parameters are: pH, DO, COD_{Mn}, BOD_5, TP, NH_4, COD, TN and petroleum. The water quality objectives are target concentrations of the selected water quality parameters to protect the most sensitive designed uses of water at the study site, such as drinking water supply and support of aquatic life. Mostafaei (2014) emphasized that the validity of CCME-WQI results strongly depends on national water quality objectives, the available data and the number of analyses examined. Thus, to obtain dependable assessment results, the Environmental Quality Standards for Surface Water in China (GB3838-2002), which was published by the Ministry of Environmental Protection in China, is used. This standard divides water quality into six classifications (Table 2). As one of the most important strategic water storage facilities in China, the water quality of the TGR needs to meet Grade III of the GB3838-2002. The Grade III standards were, therefore, chosen as water quality objectives (Table 2).

RESULTS AND DISCUSSION

Variations of water quality parameters

According to the monitoring data from eight monitoring stations from 2013 to 2015, there was one water quality parameter (TN) that exceeded the preselected water quality

Table 2 | Water quality classifications in China (GB3838-2002)

Water quality grade	Applicable water bodies
I	Sources of water bodies and national nature reserves
II	Class A water source protection areas for centralized drinking water supply, sanctuaries for rare species of fish, and spawning grounds for fish and shrimps
III	Class B water source protection areas for centralized drinking water supply, sanctuaries for common species of fish, and swimming zones
IV	Water bodies for general industrial water supply and recreational waters in which there is no direct human contact with the water
V	Water bodies for agricultural water supply and for general landscape requirements
V^+	Essentially of no value

objectives (Table 3) at least once. The TN concentrations in most monitoring stations were higher than the water quality objectives (Table 4). The average TN concentrations for monitoring stations in two tributaries, the Yipin River and the Huaxi River, were higher than that in the Wubu River. Wubu River is listed as a water source protection area for centralized drinking water supply (Table 2). Its water quality conditions are better than the other two rivers. However, TN concentrations of most sampling tests in 2014 and 2015 still exceeded the preselected water quality objectives. Anthropogenic activities, such as discharges of household and municipal sewage, are the main sources of TN in the water environment in general (Qing *et al.* 2015). In the current study, TN concentrations in the three monitoring stations of the Huaxi River were higher than those in the other monitoring stations. The Huaxi basin is mainly an urban watershed where large- and medium-sized enterprises and agricultural crop areas are densely distributed. In recent years, the population in the Huaxi basin has increased rapidly. Excessive household and municipal sewage, industrial wastewater, and agricultural fertilizers may be the main reason for the higher TN concentrations in the Huaxi River. Except for TN, NH_4, TP, BOD_5, COD, petroleum, COD_{Mn} and DO, all have monitoring values that exceed the preselected water quality objectives (Table 3) in Huaxi River. Table 5 presents the statistics of the listed water quality parameters in Huaxi River. As is shown in Table 5, water quality status in Huaxi River is quite alarming.

Table 3 | Water quality objectives used in this assessment

Water quality parameters	WQOs
pH	6–9
DO (mg L^{-1})	5
COD_{Mn} (mg L^{-1})	6
BOD_5 (mg L^{-1})	4
TP (mg L^{-1})	0.2
NH_4 (mg L^{-1})	1.0
COD (mg L^{-1})	20
TN (mg L^{-1})	1.0
Petroleum (mg L^{-1})	0.05

In this study, TN, TP, NH_4 and COD_{Mn} concentrations in Yipin River (YHQ station) and Huaxi River (SLQ station) were compared with those in Xiangxi River (XXR). XXR is the largest tributary of the TGR in Hubei Province, and also the closest tributary to the Three Gorges Dam. It has a length of 94 km, a catchment area of 2,939 km^2, and an annual average flow of 47.4 m^3/s (Li *et al.* 2014). Different from Yipin River and Huaxi River, XXR is a larger, long and narrow mountainous river draining through rural areas of Hubei Province, which has been impacted significantly by agricultural non-point source pollutions (Liu *et al.* 2013). Water quality data sets from Xiakou Station in XXR were used for the comparison (Figure 1). As is shown in Figure 1, though with the smaller watershed area and flow discharge, pollutant concentrations in Huaxi River are far larger than that in XXR, especially for TN, NH_4 and COD_{Mn}. Generally, pollutant concentrations in Yipin River are larger than that in XXR, especially for NH_4 and COD_{Mn}. Comparison results of the three rivers indicate that urban rivers are more easily being impacted by anthropogenic activities since residents are more densely

Table 4 | Statistics of TN concentrations

River	Year	Samples	HWQO	Mean (mg L^{-1})	SD	Minimum (mg L^{-1})	Median (mg L^{-1})	Maximum (mg L^{-1})
Yipin	2013	36	34	2.34	0.90	0.93	2.56	3.78
	2014	36	36	2.41	0.63	1.49	2.21	3.86
	2015	36	36	2.28	0.76	1.09	2.09	4.03
Huaxi	2013	36	25	3.14	1.76	0.87	3.41	8.17
	2014	36	24	3.82	2.12	0.92	4.67	6.03
	2015	36	27	4.14	2.33	0.69	4.34	7.47
Wubu	2013	24	0	0.92	0.04	0.81	0.93	0.97
	2014	24	16	1.83	0.75	0.85	1.99	3.22
	2015	24	23	1.39	0.26	0.81	1.38	1.93

Table 5 | Statistics of water parameters concentrations in Huaxi River

Pollutant	Year	Samples	HWQO	Mean (mg L^{-1})	SD	Minimum (mg L^{-1})	Median (mg L^{-1})	Maximum (mg L^{-1})
NH_4	2013	36	24	1.306	0.723	0.172	1.785	2.000
	2014	36	22	1.241	0.716	0.175	1.710	1.990
	2015	36	24	1.398	0.716	0.191	1.860	2.290
TP	2013	36	13	0.165	0.093	0.017	0.170	0.330
	2014	36	6	0.134	0.096	0.022	0.132	0.378
	2015	36	24	0.248	0.160	0.016	0.344	0.415
BOD_5	2013	36	14	3.7	1.143	1.8	3.5	6.1
	2014	36	11	3.5	1.018	2.0	3.3	6.7
	2015	36	15	3.7	0.864	1.7	3.8	5.5
COD	2013	36	14	20.0	7.549	10.0	18.4	39.0
	2014	36	8	18.8	6.268	10.9	17.6	39.0
	2015	36	5	17.5	4.056	10.0	17.8	34.1
Petroleum	2013	36	10	0.06	0.063	0.01	0.04	0.31
	2014	36	8	0.10	0.164	0.01	0.02	0.51
	2015	36	6	0.04	0.057	0.01	0.02	0.22
COD_{Mn}	2013	36	7	5.0	1.230	2.0	5.2	7.8
	2014	36	2	5.1	0.685	3.6	5.2	7.0
	2015	36	6	5.5	0.608	4.3	5.5	6.8
DO	2013	36	4	6.83	1.262	4.0	6.95	9.2
	2014	36	2	7.26	1.293	2.9	7.57	10.0
	2015	36	1	6.91	1.011	4.8	6.84	9.3

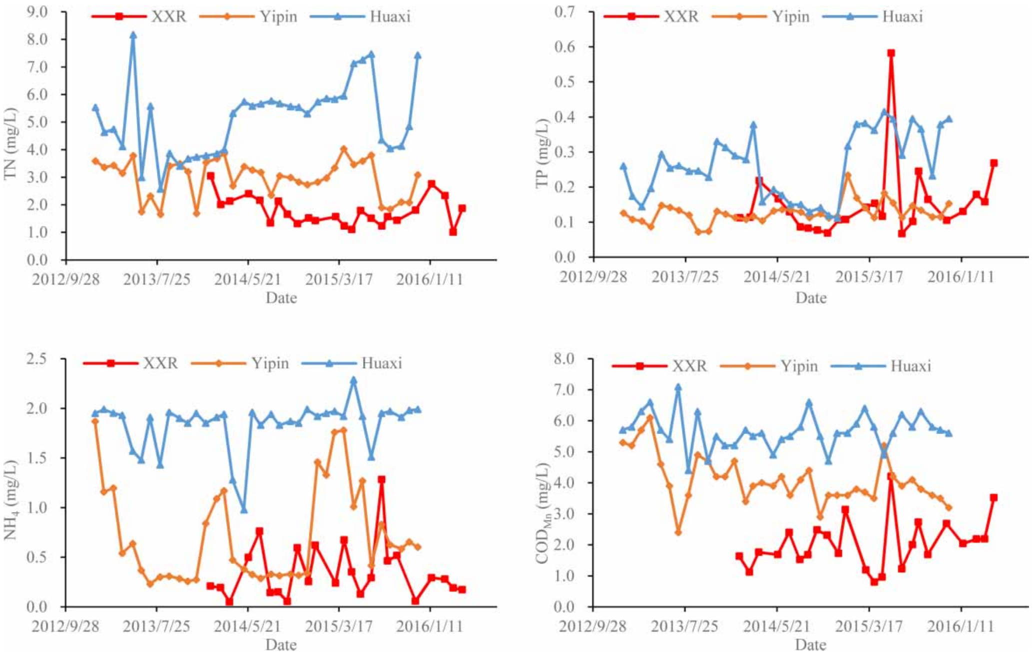

Figure 1 | Comparison of water quality parameters of Yipin, Huaxi and Xiangxi River (XXR).

distributed, and industrial activities are far more rampant, especially with the development of urbanization in China.

Water quality assessment using the CCME-WQI and NPI

The CCME-WQI values for each station in the time period 2013–2015 are listed with their corresponding water quality status in Table 6. The results show that the water quality conditions of the Wubu River are quite good with respect to China's Grade III limit. The assessment results of NPI in Wubu River indicate that the river was slightly polluted in 2014 and 2015, induced by TN, which exceeded the preselected water quality objectives (Table 3). Water quality conditions in the upstream sections (CSZ and NHCK) were good in Yipin and Huaxi River. However, when the river drained through urban areas, water quality conditions deteriorated due to the excessive release of household and municipal sewage, and industrial wastewater, especially for Huaxi River. Analyzing water quality parameters in a tributary of Huaxi River (between NHCK and JLY), it was found that the pollution status in Huaxi basin was quite severe (Figure 2), and strict river management is needed to better manage water resources in this area, even though the overall water quality in the TGR remained stable and was ranked as 'good' (Zhao *et al.* 2016).

Generally, the assessment results of the NPI approach were consistent with that of the CCME-WQI approach (Table 6). In some stations, there is a slight difference. For example, CCME-WQI values are nearly the same for 2013 and 2014 for the JLY station in Huaxi River. However, the NPI values are quite different (Table 6). The number of failed variables are the same for 2013 and 2014, and the percentage of failed tests in 2013 is larger than that in 2014. However, the $(P_i)_{MAX}$ value in 2014 (10.2) is far larger than that in 2013 (5.36), which results in a larger NPI value in 2014. Both the dominant water quality parameter and the average contribution of all environmental factors are considered for the NPI method. However, this method overemphasized the influence of the most serious pollutant factor, which has also been reported by Ji *et al.* (2016). Therefore, the comprehensive score will increase dramatically in cases where the index value for one evaluation factor is much larger than those of the others. Hence, there exists a potential issue that the assessment results may disagree with the overall water quality conditions in a certain water body. In this study, there was no obvious variation of water quality conditions in Huaxi River from 2013 to 2014 (Table 5). Thus, the assessment results of NPI in the JLY station may be misleading. This method should be used with caution for water resources managers.

The CCME-WQI approach has many advantages. First, it can be used to effectively evaluate the overall water quality status and health of aquatic systems. Additionally, it conducts water quality evaluation by a variety of typical evaluation indicators rather than using the worst factor, and therefore the assessment results of water quality conditions are dependable. According to the assessment results of this study, the CCME-WQI approach can be

Table 6 | CCME-WQI with corresponding water quality status for the three rivers during 2013–2015

		2013				2014				2015			
		CCME-WQI		NPI		CCME-WQI		NPI		CCME-WQI		NPI	
River	Stations	Value	Status	Value	Status	Value	Status	Value	Status	Value	Status	Value	Status
Yipin	CSZ	90.37	Good	1.37	II	89.68	Good	1.37	II	89.82	Good	1.35	II
	BJDK	76.66	Fair	1.82	II	82.36	Good	1.72	II	83.16	Good	1.62	II
	YHQ	56.66	Marginal	2.32	II	73.02	Fair	2.72	III	69.19	Fair	2.18	II
Huaxi	NHCK	93.47	Good	0.91	II	100.0	Excellent	0.79	I	93.24	Good	0.94	II
	JLY	33.90	Poor	2.92	III	38.29	Poor	4.84	IV	41.86	Poor	4.01	III
	SLQ	35.48	Poor	3.45	III	38.30	Poor	4.61	IV	35.30	Poor	4.31	IV
Wubu	JQ	100.0	Excellent	0.74	I	91.24	Good	1.26	II	90.71	Good	1.03	II
	ZC	100.0	Excellent	0.77	I	90.29	Good	1.50	II	90.85	Good	1.13	II

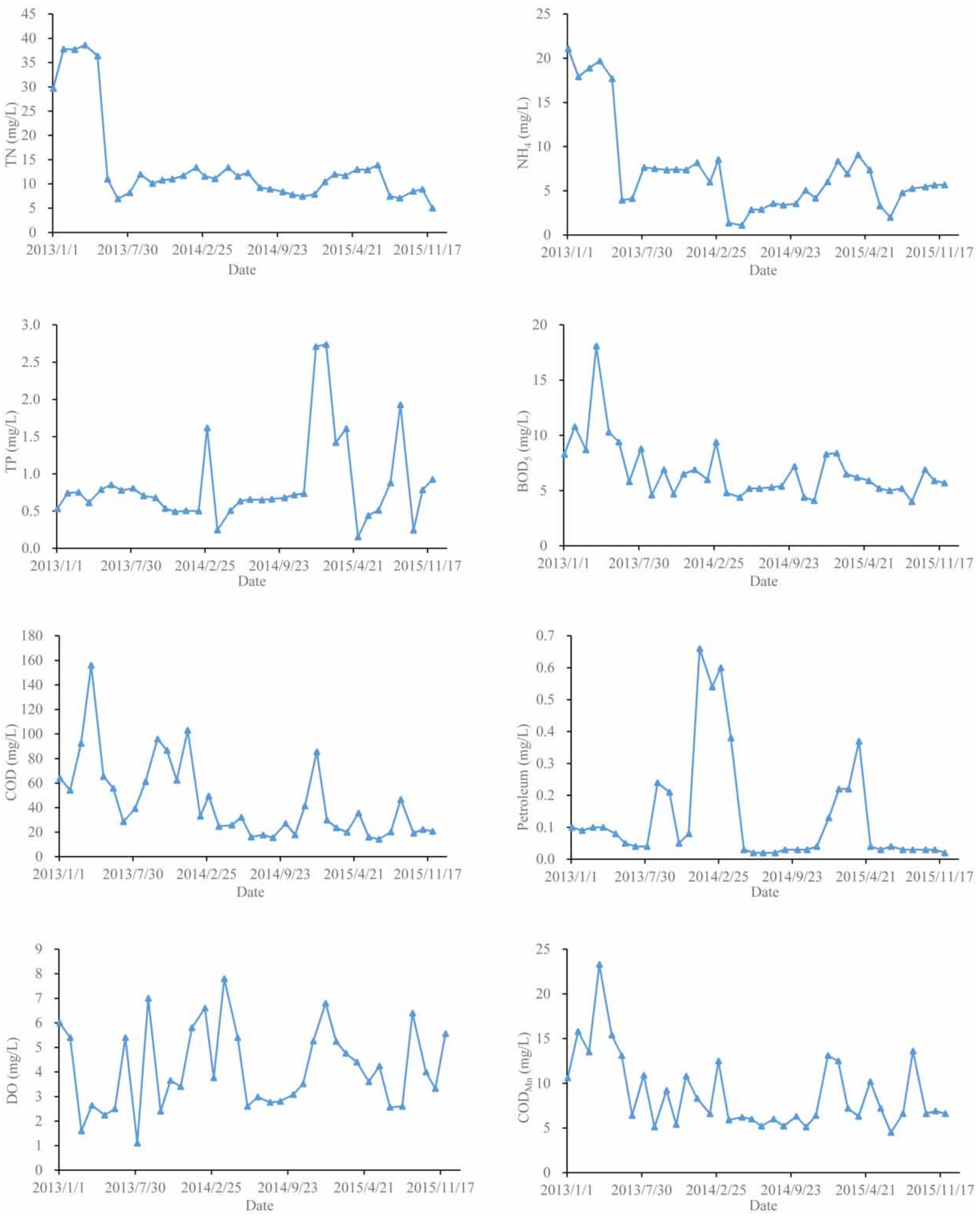

Figure 2 | Concentrations of water quality parameters in a tributary of Huaxi River.

used to effectively evaluate whether the overall water quality conditions can meet the specified water quality objectives, and provide reference for decision-makers on water resources management.

CONCLUSIONS

Water quality conditions in three urban tributaries of the TGR were evaluated with the CCME-WQI and NPI approaches using monitoring data from 2013 to 2015. The CCME-WQI values indicated that the water quality conditions in the Wubu River are quite good during the period 2013–2015. Assessment results of the NPI method in Wubu River indicate that the river was slightly polluted in 2014 and 2015, induced by TN, which exceeded the preselected water quality objectives. Water quality conditions in the upstream sections of Yipin and Huaxi River were good. However, when the river drained through urban areas, water quality conditions greatly deteriorated due to the excessive release of household and municipal sewage, and industrial wastewater, especially for Huaxi River. The pollution status in Huaxi basin is quite severe, and strict river management is needed to better manage water resources in this area. Generally, assessment results of the NPI approach consistent with that of the CCME-WQI approach. However, the NPI method tends to overemphasize the influence of the most serious pollutant factor. Therefore, the assessment result will increase dramatically in situations where the index value for one evaluation factor is much larger than those of the others. This method should be used with caution for water resources managers. For the CCME-WQI approach, it can be used to effectively evaluate the overall water quality conditions, and provide reference for decision-makers on water resources management.

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