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Spatiotemporal variation characteristics and source identification of water pollutants in Shayinghe River basin

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Abstract

To understand the spatiotemporal variation characteristics and the sources of water pollutants in the Shayinghe River Basin, water quality monitoring data of the five water quality indexes (biochemical oxygen demand: BOD_5, permanganate index: COD_{Mn}, ammonium nitrogen: NH_3–N, total phosphorus: TP and dissolved oxygen: DO) were collected from 11 monitoring stations and divided into 6 categories (classes I, II, III, IV, V and inferior class V). The spatiotemporal distribution characteristics of the water pollutants were comprehensively identified by the water pollution index method (WPI), Mann-Kendall trend test, cluster analysis and box-plot analysis method, and the effects of the pollution source, runoff and sluice regulation were analyzed for water pollutants. The results indicated that the water quality standard of classes mainly belonged to class IV or above in Shayinghe River Basin, accounting for about 70%, but the water quality standard reached class I and class II for less than 15%. The water pollutants presented a significant decreasing trend, and the NH_3-N and TP were the key control indexes for the monitoring stations in the Shayinghe River Basin. The exceeding rates of WPI values showed a significantly decreasing trend at Baidukou, Mawan, Huangqiao, Zhoukou Sluice, Jieshou, Fuyang Sluice and Yingshang Sluice by controlling the NH_3-N and TP. The WPI values showed obvious variations in January 2011, March 2013 and October 2014 at the Baisha Reservoir, Mawan and Chengwan. The WPI values were divided into two major categories with respect to time. The non-flood season should be used as the key period for water quality management and control; the variability of WPI values was relatively large from January to June, November, and December, and the variability of WPI values was relatively low from July to October. The monitoring sections were spatially divided into three major categories. The WPI values had the greatest variability at Huangqiao and a relatively small variability at Baisha Reservoir, Mawan and Chengwan. The study results could provide the scientific basis for realizing targeted pollution source treatment, improving the effectiveness of water quality management and ecological environment, and a theoretical foundation for pollution control and water quality improvement in the Shayinghe River Basin.

KEYWORDS

cluster analysis, pollution sources, Shayinghe River, Spatio-temporal variation characteristics, water pollution index

1 | INTRODUCTION

As the largest tributary of the Huaihe River Basin, the water pollution of Shayinghe River Basin poses a serious threat to the water quality in the mainstream of the Huaihe River (Gao, Li, & Zhao, 2010; Ye, Gao, & Hu, 2014). In recent years, water environment pollution has become a serious problem with the rapid development of economy and society in the Shayinghe River Basin, which has not only restricted the development of industry and agriculture but has also seriously affected the domestic water of downstream residents (He, He, Wang, Zhang, & Bi, 2019; Hu, Xu, Wang, & Liu, 2018).

River water quality assessment is the foundation and guarantee for water quality management, which reflects the water quality classification and pollution index and shows the spatiotemporal variations of water quality (Liu & Wu, 2014). Water quality assessment is an analytical method to quantitatively describe the degree of water quality pollution with specific methods (Jing et al., 2019). At present, river water quality assessment methods mainly include water pollution index (WPI) (Liu, Zheng, Fu, Luo, & Wang, 2013), artificial neural network (Cha, Lu, Zhai, & Zhang, 2018; Xia & Chen, 2015), matter-element analysis (Chen & Yang, 2016), fuzzy mathematics assessment (Li, Zou, & An, 2016), principal component analysis (Li, Li, Shi, Zhao, & Quan, 2018), the single factor index assessment method (Liu, Gu, Li, & Wu, 2019) and water quality index method (Tang & Wang, 2019). WPI involves simplifying the concentration of the water quality pollution index into a single index value. It has the advantages of convenient calculation, high accuracy, intuitive results, and good comparability and grading to represent the degree of water pollution (Gao, Zou, & Sun, 2019; Liu & Liu, 2005). Some studies have shown that the spatial and temporal distribution and variation of water quality were identified with the water pollution index and hierarchical cluster analysis method in the mainstream of the Xiangjiang River and in the middle and downstream of Hanjiang River (Jing et al., 2019; Liu et al., 2013). A fuzzy improved water pollution index was proposed based on a fuzzy inference system and water pollution index, and water quality assessment was applied in the Qu River (Li, Zou, et al., 2016). Sun, Wang, and Qi (2018) evaluated the water quality in the mainstream of the Yellow River with an improved comprehensive water quality index method. The spatiotemporal variations of water quality were evaluated based on the water pollution index on the inter-annual scale, and the major pollution indexes were revealed in a shallow lake of an arid area (Zhang et al., 2019a). The WPI of Poyang Lake was evaluated using the principal component analysis method (Liu, Huang, Kang, Du, & Cao, 2019). In general, the water pollution index method is widely used in water quality evaluation assessment.

Rivers are an important factor for the sustainable development of regional ecological environment, which exhibit significant temporal and spatial differences in climate and meteorology, topography and landforms, human activities, and industrial and agricultural production. River water quality exhibits spatiotemporal heterogeneity because the runoff and pollutant concentrations are different in different time and space (Tang, Lu, & Wu, 2019). River water quality status and management need to be comprehensively understood to identify the spatial and temporal distribution characteristics of river water quality and pollution sources (Qiu, Lu, Xu, & Wang, 2017). At present, multivariate statistical analysis methods are used to analyze the temporal and spatial similarity and differences of water pollutants (Ma, Wang, & Liao, 2015; Sun, Yang, Chen, Hou, & Zheng, 2019; Zhu et al., 2018), such as the variance analysis method, principal component analysis, factor analysis method, Mann-Kendall trend test and cluster analysis. The application of these methods has played an important role in understanding the temporal and spatial characteristics and pollution sources of the water quality of rivers such as the Kuwait Bay (Al-Mutairi, Abahussain, & El-Battay, 2014), Lake Hachiro (Hayakawa, Ikeda, Tsushima, Ishikawa, & Hidaka, 2015), upper reaches of Chishui River (Teng, Ding, Li, Jing, & Liu, 2016), Poyang Lake Basin (Li, Ge, Hu, Liu, & Zhou, 2016), Yellow River Basin (Lv & Mu, 2017) and Huaihe River Basin (Zhai, Xia, & Zhang, 2014). A structural dataset was established for better understanding of water quality in the Nakdong River Basin by multivariate statistical techniques, which could provide simpler but clearer explanations without losing important information (Han, Kim, & Kim, 2009). The pollution sources were specifically and accurately identified using cluster analysis and backward discriminant analysis in the Qinhe River Basin (Wang et al., 2012). The spatiotemporal characteristic variations of water quality and its influencing factors were identified in the Jiulong River Basin using the geographical information system and multivariate statistical analysis (Huang et al., 2012). Furthermore, the time series analytic method was adopted to analyze its time variation rule of water pollutant concentration, and the impact factors of water pollution were analyzed by correlation analysis in the Changhu Lake (Yu, Xu, & Xu, 2016). The spatiotemporal distribution and sources of nitrogen were analyzed using a geographical information system and box-plot analysis method in 22 rivers in Tieling City (Yang, Lei, Qiao, & Meng, 2018).

In this study, to comprehensively evaluate the current situation of the water environment, spatiotemporal distribution characteristics, and variation rules under the influence of human activities in the Shayinghe River Basin, cluster analysis, Mann-Kendall trend test and box-plot analyses were used based on the water pollution index. The main sources of pollutants were analyzed to more accurately present the characteristics of pollution sources and identify the key pollution sources. We provide the scientific basis for realizing targeted pollution source treatment, improving the effectiveness of water quality management, water quality status and ecological environment in Shayinghe River Basin.

2 | MATERIALS AND METHODS

2.1 | Study area

The Shayinghe River (111°55′28″~116°19′36″, 32°36′36″~34°58′22″) is the largest tributary of the Huaihe River Basin that originated from Songshan, Dengfeng County, Henan Province, and its tributaries include Shahe River, Yinghe River, Jialuhe River, Beiruhe River, Fenquanhe River, Xincaihe River and Hetz River (Zhang, Shao, Ye, Xing, & Xia, 2016). The total length of the Shayinghe River is 620 km, including 410 km in the Henan Province and 210 km in the Anhui Province. The basin area is 36,728 km^2, which covers 10 cities—Zhengzhou, Kaifeng, Xuchang, Zhoukou, Luoyang, Pingdingshan, Nanyang, Luohe, Zhumadian and

Fuyang City (Figure 1). The total population is 34 million, cultivated land is 3.99 million hectares and the effective irrigation area is 1.16 million hectares in the Shayinghe River Basin (He et al., 2019; Huang, Xie, Zhou, et al., 2019; Luo & Zuo, 2019). The self-produced water resources of the Shaying River Basin only account for 3.4% of that of China, but the emissions of sewage and COD are 8.4 and 7.8%, respectively (Dou, Wang, & Li, 2017). The Shayinghe River Basin is an important source of water for navigation and agricultural irrigation in the Huaihe River Basin, and an important grain production base and central plains economic zone.

2.2 | Data description

The research data were mainly obtained from the environmental monitoring center of Henan and the monitoring center of the Huaihe River Water Resources Protection Bureau. Five water quality indexes (biochemical oxygen demand: BOD_5, permanganate index: COD_{Mn}, ammonium nitrogen: NH_3–N, total phosphorus: TP, and dissolved oxygen: DO) were obtained from 11 monitoring stations in the Shayinghe River Basin—Chenqiao, Baidukou, Baisha Reservoir, Mawan, Chengwan, Huangqiao, Zhoukou Sluice, Huaidian Sluice, Jieshou, Fuyang Sluice and Yingshang Sluice (Figure 1). The Jieshou is the provincial boundary section of the Henan Province and Anhui Province, and Huangqiao is the hydrological station in the Yinghe River. Zhoukou Sluice, Huaidian Sluice, Fuyang Sluice and Yingshang Sluice are the main sluices of the Shayinghe River Basin, which perform the functions of flood control, and waterlogging, irrigation water supply, navigation, breeding and ecological protection.

The monitoring data of the water quality indexes from 2009 to 2017 were collected at Chenqiao, Baidukou, Baisha Reservoir, Mawan and Chengwan; the monitoring data of the water quality indexes from 2003 to 2012 were collected at Huangqiao, Zhoukou Sluice, Huaidian Sluice, Fuyang Sluice and Yingshang Sluice; and the monitoring data of the water quality indexes from 2003 to 2017 were collected at Jieshou. The monitoring frequency of water quality indexes was once a week, and the water quality monitoring data were compiled into monthly average values. All elements were tested following national standards of water-quality testing (MEE, 1989a, 1989b, 2009a, 2009b, 2009c), such as the BOD_5, NH_3-N, TP and DO are determined by the dilution and seeding method, Nessler's reagent spectrophotometry method, ammonium molybdate spectrophotometric method and Electrochemical probe method, respectively. The water quality monitoring data were analyzed according to the environmental functions and protection objectives of surface water in the Chinese environmental quality standards for surface water (GB 3838–2002) (China's State Environmental Protection Administration, 2002).

2.3 | Research methods

2.3.1 | Water pollution index method

The water pollution index method is based on the single factor index assessment method recommended by the Chinese environmental quality standards for surface water (GB 3838–2002).

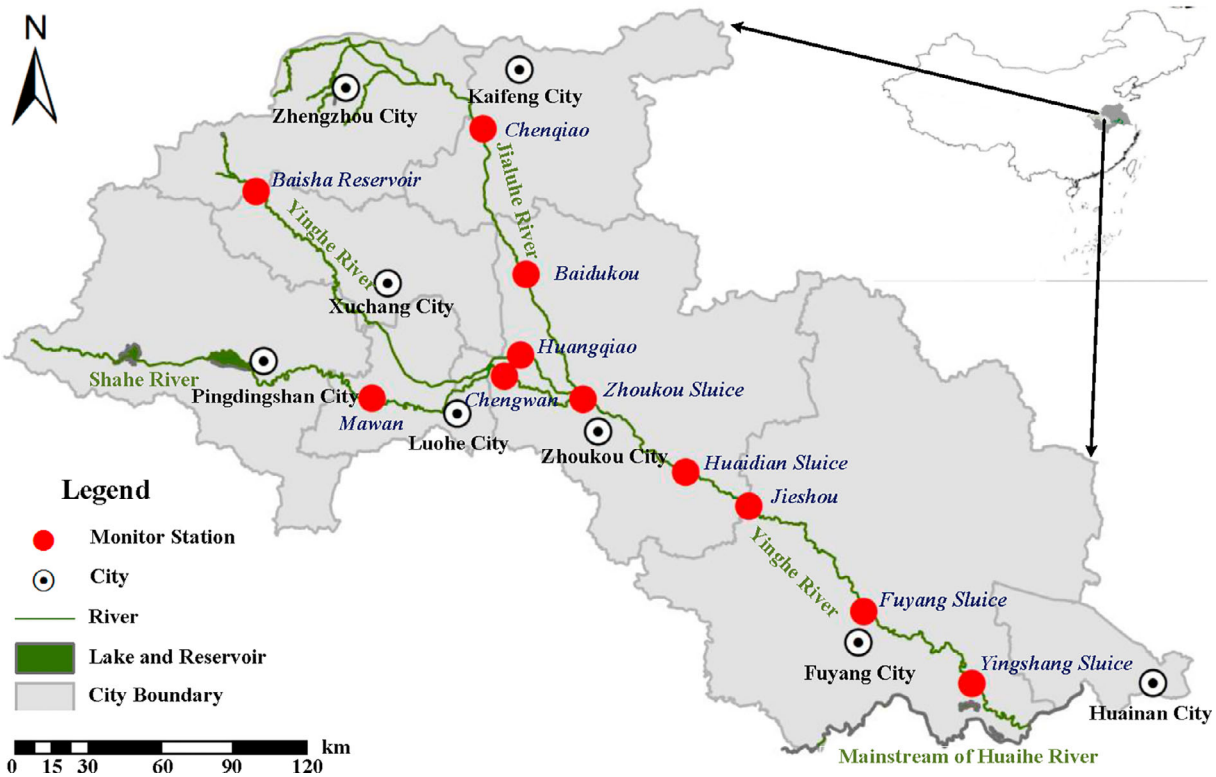

FIGURE 1 Location of study area and water quality monitoring stations

In this study, the WPI values were calculated based on five water quality indexes. The maximum WPI value of five water quality indexes was taken as the WPI value of the monitoring station (Jing et al., 2019; Liu et al., 2013; Liu & Wu, 2014; Wang, Wu, Zhao, Qin, & Peng, 2015). The comparison between WPI values and Chinese environmental quality standards for surface water (GB 3838–2002) is shown in Table 1.

If the water quality result of a single factor index assessment does not exceed the water quality standard of class V, the calculation formula of the WPI value is shown in Equation (1). If the concentration of DO is greater than or equal to 7.5 mg L^{-1}, the WPI_{DO} is 20; if the concentration of DO is greater than or equal to 2 mg L^{-1} or less than 7.5 mg L^{-1}, the calculation formula of WPI_{DO} is shown in Equation (2). If the water quality result of single factor index assessment exceeds the water quality standard of class V, the calculation formula of the WPI value is shown in Equation (3).

$$WPI(i) = WPI_t(i) + \frac{WPI_h(i) - WPI_t(i)}{C_h(i) - C_t(i)} \times [C(i) - C_t(i)]\ C_t(i) < C(i) \le C_h(i) \tag{1}$$

$$WPI(i) = WPI_t(i) + \frac{WPI_h(i) - WPI_t(i)}{C_t(i) - C_h(i)} \times [C_t(i) - C(i)] \tag{2}$$

$$WPI(i) = 100 + \frac{C(i) - C_5(i)}{C_5(i)} \times 40 \tag{3}$$

where $C(i)$, $C_t(i)$, $C_h(i)$ and $C_5(i)$ are the water quality monitoring concentration values, the lower limit concentration value of water quality standard, the upper limit concentration value of the water quality standard and the concentration limit value of class V standard in the Chinese environmental quality standards for surface water (GB 3838–2002), respectively. $WPI(i)$, $WPI_t(i)$ and $WPI_h(i)$ are the WPI value corresponding to water quality concentration value. If the values of the two water quality standard classes in the Chinese environmental quality standards for surface water (GB 3838–2002) are the same, the interpolation calculation is based on the interval of low score values.

2.3.2 | Analysis method of water pollution index assessment

(1) Proportion of monitoring stations.

$$w = N_k / N \times 100\% \tag{4}$$

where w is the proportion of monitoring stations, %; N_k is the number of monitoring stations that meet the requirements of water quality class k; and N is the total number of monitoring stations.

(2) Exceeding rate.

$$\eta = m' / M \times 100\% \tag{5}$$

where η is the exceeding rate, %; m' is the number of months when the water quality of the monitoring station is worse than the water quality target; and M is the total number of months in the study period.

2.3.3 | Mann-Kendall trend test

The Mann-Kendall trend test (Kendall, 1975; Mann, 1945) is a nonparametric statistical test, which means it is a distribution-free test. The Mann-Kendall trend test is not disturbed by a few outliers and is applicable to data testing of non-normal distribution hydrology, meteorology and water-quality factor data (Bian et al., 2017; Rahman, Lou, & Sultana, 2017). The zero hypothesis (H_0) of the Mann-Kendall trend test is the time series x_i' (i' = 1, 2, …, n) and is an independent random variable with the same distribution of samples; alternative hypothesis (H_1) is a bilateral test, assuming that x_i' and x_j ($j \le n$ and $i' \neq j$) have different distributions. The advantage of the Mann-Kendall trend test is that it can test the linear or nonlinear variation trends, and its extended accuracy has been widely used in water quality trend analysis (Bouza-Deaño, Ternero-Rodríguez, & Fernández-Espinosa, 2008). Z_{MK} is the variation trend of time series data, which exhibits an increasing trend if Z_{MK} is greater than zero and a decreasing trend if Z_{MK} is less than zero. When $|Z_{MK}| > Z_{(1-\alpha/2)}$, the null hypothesis is rejected, and there is a significant trend in the time series data. Values of $Z_{(1-\alpha/2)}$ can be found by the standard normal distribution table; when the level of α = 5% is significant, the corresponding value is 1.96 (Wei & Deng, 2014).

2.3.4 | Cluster analysis

Cluster analysis is a widely used multivariate statistical analysis technology, which classifies many characteristics of a batch of data cases

TABLE 1 The comparison between WPI values and Chinese environmental quality standards for surface water (GB 3838–2002)

Index \ Water quality class	Class I	Class II	Class III	Class IV	Class V	Inferior Class V
WPI	20	20 < WPI≤40	40 < WPI≤60	60 < WPI≤80	80 < WPI≤100	WPI > 100
BOD_5	≤3	≤3	≤4	≤6	≤10	>10
COD_{Mn}	≤2	≤4	≤6	≤10	≤15	>15
NH_3–N	≤0.15	≤0.5	≤1.0	≤1.5	≤2.0	>2.0
TP	≤0.02	≤0.1	≤0.2	≤0.3	≤0.4	>0.4
DO	≥7.5	≥6	≥5	≥3	≥2	<2

or variables according to the distance of the relationship. A frequently-used cluster analysis method is hierarchical clustering analysis, which involves treating each individual participant in clustering as a class and gradually aggregating them according to the distance or similarity between the two classes until they become a single class (Tang et al., 2019; Xu, Xu, Tang, Yu, & Cheng, 2012). There are two quantitative description methods of distance and proximity, one is the distance between samples, such as the Euclidean distance, Euclidean square distance, Chebyshev distance and Block distance, and the other is the distance between the sample and subclass, such as the farthest neighbor method, barycenter clustering method, between-groups linkage method and square sum of deviations method. In this study, the water quality indexes in time and space scales were analyzed using the hierarchical clustering analysis in the SPSS21.0 software. The clustering mode was the between-groups linkage method, and the distance measurement mode was the Euclidean square distance (Jing et al., 2019; Zhou, Guo, Huang, Yu, & Hao, 2007). The temporal–spatial distribution characteristics of the water quality in the river basin could be analyzed by cluster analysis, and the clustering was carried out according to monitoring time and location of monitoring stations in the water quality assessment (Zhang et al., 2019).

2.3.5 | Box-plot analysis method

Box-plot analysis method is a simple tool to describe statistics and can visually represent data with shapes by a simple combination graph. It is used to reflect the central position and spread range of one or more groups of continuous quantitative data distribution (Tareen et al., 2019). The biggest advantage of box-plot is that they are not affected by outliers and can describe the discrete distribution of data in a relatively stable manner. The box-plot is used to analyze the water quality condition, which clearly reflects the variation regulation of the complex monitoring data (Teng et al., 2016).

3 | RESULTS AND ANALYSIS

3.1 | The correlation analysis of water quality indexes

The Pearson correlation coefficients of water quality indexes for the 11 water quality monitoring stations in the Shayinghe River Basin were calculated, as shown in Table 2. The correlation and statistical characteristics of water quality indexes could clarify the background relationships of the water quality indexes before the transformation using the water pollution index method.

Certain correlations were observed between the water quality indexes in the Shayinghe River Basin according to Table 2. The results show that there were significant positive correlations between COD_{Mn}, NH_3-N and BOD_5, and there were no significant correlations between TP, DO and BOD_5. There were the significant positive correlations between NH_3-N, TP and COD_{Mn}, and there was no significant correlation between COD_{Mn} and DO. There was a significant positive correlation between NH_3-N and TP, but there was no significant correlation between NH_3-N and DO. There was no significant correlation between TP and DO. In addition, the concentrations of BOD_5, NH_3-N and TP exhibited considerable fluctuations according to the monthly average change range in the Shayinghe River Basin. The extreme ratios (maximum/minimum) were 13.97, 48.56 and 12.72, respectively. The fluctuations of COD_{Mn} and DO concentrations were relatively small, and the extreme ratios (maximum/minimum) were 7.75 and 2.93, respectively.

3.2 | Spatiotemporal status distribution of water quality

To evaluate the water quality in Shayinghe River Basin, the proportion of monitoring stations for the water quality standard of classes during 2009–2011 was calculated based on the Equation (4) (Figure 2). The results showed that the water quality standard of classes mainly belonged to class IV or above in the Shayinghe River Basin, accounting for about 70%, but the water quality standard of classes reached Class I and Class II for less than 15%. For the perspective of annual distribution, the linear change rate of WPI values was positive in the flood season (June–September), and the proportion of water quality standard of class IV or above was 66%; the linear change rate of WPI values was negative in the non-flood season (January–May and October–December), and the proportion of water quality standard of Class IV or above was 73%, which indicated that the water quality was generally poor in the Shayinghe River Basin, and the water quality in non-flood season was obviously inferior to that in the flood season.

The control indexes of water quality were TP, NH_3-N and BOD_5 in the flood season; the months with TP as the control index accounted for about 47.22% (WPI_{TP} was the largest); the months with

TABLE 2 The correlation and statistical characteristics of water quality indexes

Water quality index	BOD_5	COD_{Mn}	NH_3-N	TP	DO
BOD_5	1				
COD_{Mn}	**0.344**	1			
NH_3-N	**0.298**	**0.430**	1		
TP	0.044	**0.271**	**0.395**	1	
DO	−0.058	−0.125	−0.002	−0.06	1

Note: The bold fonts indicated a significant correlation at the 0.05 level (bilateral).

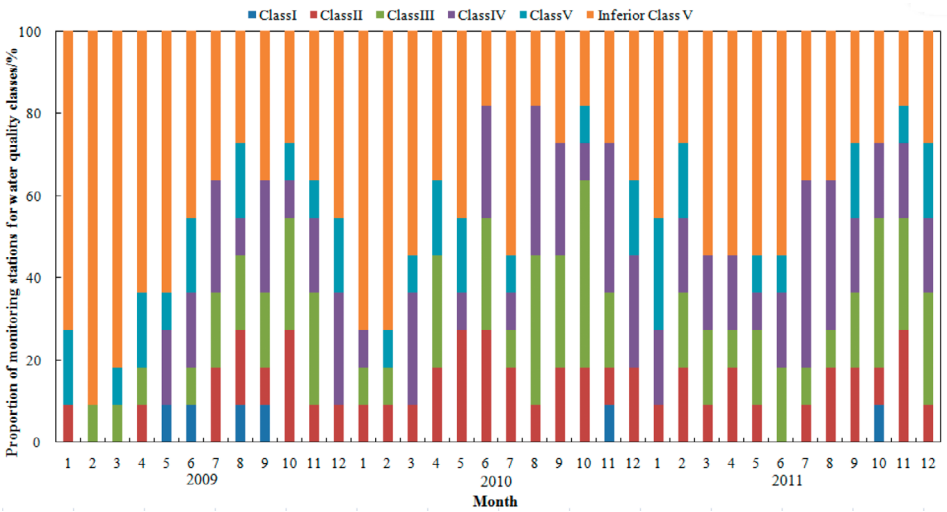

FIGURE 2 Proportion of monitoring stations for water quality classes during 2009–2011 in Shayinghe River Basin

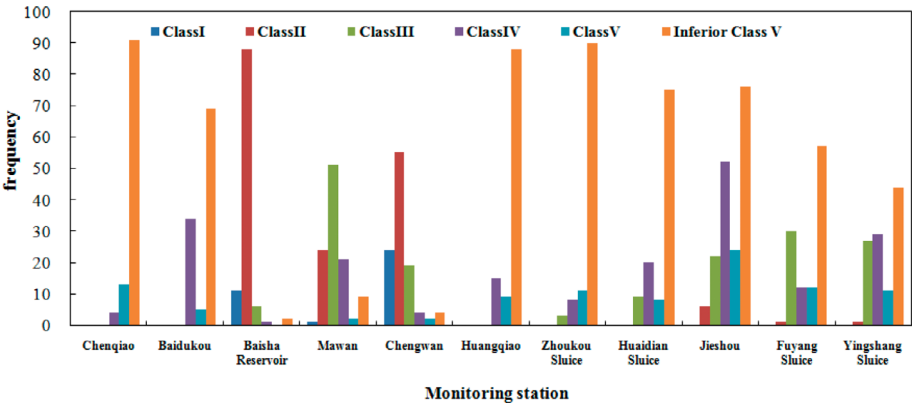

FIGURE 3 The frequencies of water quality classes basing on the WPI in Shayinghe River Basin

NH_3-N as the control index accounted for about 28.24% (WPI_{NH_3-N} was the largest); and the months with BOD_5 as the control index accounted for about 13.43% (WPI_{BOD_5} was the largest). The control indexes of water quality were TP and NH_3-N in the non-flood season, the months with NH_3-N as the control index accounted for about 77.85% (WPI_{NH_3-N} was the largest) and the months with TP as the control index accounted for about 16.01% (WPI_{TP} was the largest).

Overall, the water quality showed an obvious improvement trend in the Shayinghe River Basin, especially for the inferior Class V. The key water quality control indexes were different in flood season and non-flood season. TP was the key control index in the flood season, and the NH_3-N was the key control index in the non-flood season, which may be because the river had more runoff and faster flow speed in the flood season, and the dilution and degradation of NH_3-N were stronger in the flood season than in the non-flood season.

In Figure 3, the frequencies of water quality classes were calculated in space based on the WPI in Shayinghe River Basin. The water quality standard of classes mainly belonged to Class II at Baisha Reservoir and Chengwan, and the frequencies of water quality that reached Class II were 88 and 55, respectively. The water quality standard of classes mainly belonged to Class III at Mawan, and the frequency of water quality that reached Class III was 51. The water pollution was serious at Chenqiao, Baidukou, Huangqiao, Zhoukou Sluice, Huaidian Sluice, Jieshou, Fuyang Sluice and Yingshang Sluice, where the water quality standard mainly belonged to the inferior Class V, and the frequencies of water quality that reached the inferior class V were 91, 69, 88, 90, 75, 76, 57 and 44, respectively. Zhoukou Sluice is located at the intersection of Shahe River, Yinghe River and Jialuhe River, and the water quality standard of classes mainly belonged to Class IV or above, accounting for about 97%. Thus, the water quality situation reflected the water pollution condition in the upper reaches of the Shayinghe River. Yingshang Sluice is the main control sluice of Shayinghe River flowing into the mainstream of Huaihe River, in which the water quality standard mainly belonged to Class IV or above, accounting for about 75%.

According to the water environment function zoning in Henan Province and Hubei Province, the water quality target and the main exceeding water quality indexes at 11 monitoring stations are shown in Table 3, and the spatial distribution of rate of exceeded standard water quality based on the WPI in Shayinghe River Basin is shown in Figure 4.

In Figure 4, the exceeding rates of WPI values were less than 30% at Baisha Reservoir, Chengwan and Mawan; the exceeding rates of WPI values were 68.52, 72.32 and 75% at Baidukou, Fuyang Sluice and Yingshang Sluice, respectively; the exceeding rates of WPI values

exceeded 80% at Chenqiao, Huangqiao, Zhoukou Sluice, Huaidian Sluice and Jieshou. For Baidukou, the exceeding rates of $WPI_{COD_{Mn}}$ and WPI_{NH_3-N} were 25.93 and 68.52%, respectively, and the control index of water quality was NH_3-N at Baidukou. For Chenqiao, the exceeding rates of $WPI_{COD_{Mn}}$ and WPI_{NH_3-N} were 95.37 and 96.30%, respectively, and the control indexes of water quality were COD_{Mn} and NH_3-N at Chenqiao. For Huangqiao, the exceeding rates of $WPI_{COD_{Mn}}$, WPI_{NH_3-N} and WPI_{TP} were 46.43, 73.21 and 53.57%, respectively, and the control index of water quality was NH_3-N at Huangqiao. For Zhoukou Sluice, the exceeding rates of WPI_{NH_3-N} and WPI_{TP} were 75 and 64.29%, respectively, and the control index of water quality was NH_3-N at Zhoukou Sluice. For Huaidian Sluice, the exceeding rates of WPI_{BOD_5}, $WPI_{COD_{Mn}}$, WPI_{NH_3-N} and WPI_{TP} were 43.75, 58.93, 72.32 and 84.14%, respectively, and the control index of water quality was TP at Huaidian Sluice. For Jieshou, the exceeding rates of WPI_{BOD_5}, $WPI_{COD_{Mn}}$, WPI_{NH_3-N} and WPI_{TP} were 41.07, 38.33, 57.22 and 65.18%, respectively, and the control index of water quality was TP at Jieshou. For Fuyang Sluice, the exceeding rates of WPI_{NH_3-N} and WPI_{TP} were 59.82 and 53.57%, respectively, and the control indexes of water quality were NH_3-N and TP at Fuyang Sluice. For Yingshang Sluice, the exceeding rates of WPI_{NH_3-N} and WPI_{TP} were 50.89 and 47.32%, respectively, and the control indexes of water quality were NH_3-N and TP at Fuyang Sluice. Overall, NH_3-N and TP were the key control indexes for the monitoring stations in the Shayinghe River Basin, which may be related to the pollutant discharge along the bank of Shayinghe River.

To verify the impact of NH_3-N and TP for the water quality in Shayinghe River Basin, which was assumed that through the process and treatment, NH_3-N and TP satisfied the water quality requirements of the monitoring stations (Table 3), and the spatial distribution of

TABLE 3 The water quality target and the main exceeding water quality indexes at 11 monitoring stations

Monitoring stations	Water quality target	Main exceeding water quality index	
		Current situation	Hypothetica scenario
Chenqiao	Class IV	COD_{Mn}, NH_3-N	COD_{Mn}
Baidukou	Class IV	COD_{Mn}, NH_3-N	COD_{Mn}
Baisha reservoir	Class II	COD_{Mn}, NH_3-N	COD_{Mn}
Mawan	Class III	COD_{Mn}, NH_3-N	COD_{Mn}
Chengwan	Class III	COD_{Mn}, NH_3-N	COD_{Mn}
Huangqiao	Class IV	COD_{Mn}, NH_3-N, TP	COD_{Mn}
Zhoukou sluice	Class IV	COD_{Mn}, NH_3-N, TP	COD_{Mn}
Huaidian sluice	Class III	BOD_5, COD_{Mn}, NH_3-N, TP	BOD_5, COD_{Mn}
Jieshou	Class III	BOD_5, COD_{Mn}, NH_3-N, TP	BOD_5, COD_{Mn}
Fuyang sluice	Class III	BOD_5, COD_{Mn}, NH_3-N, TP	BOD_5, COD_{Mn}
Yingshang sluice	Class III	BOD_5, NH_3-N, TP	BOD_5

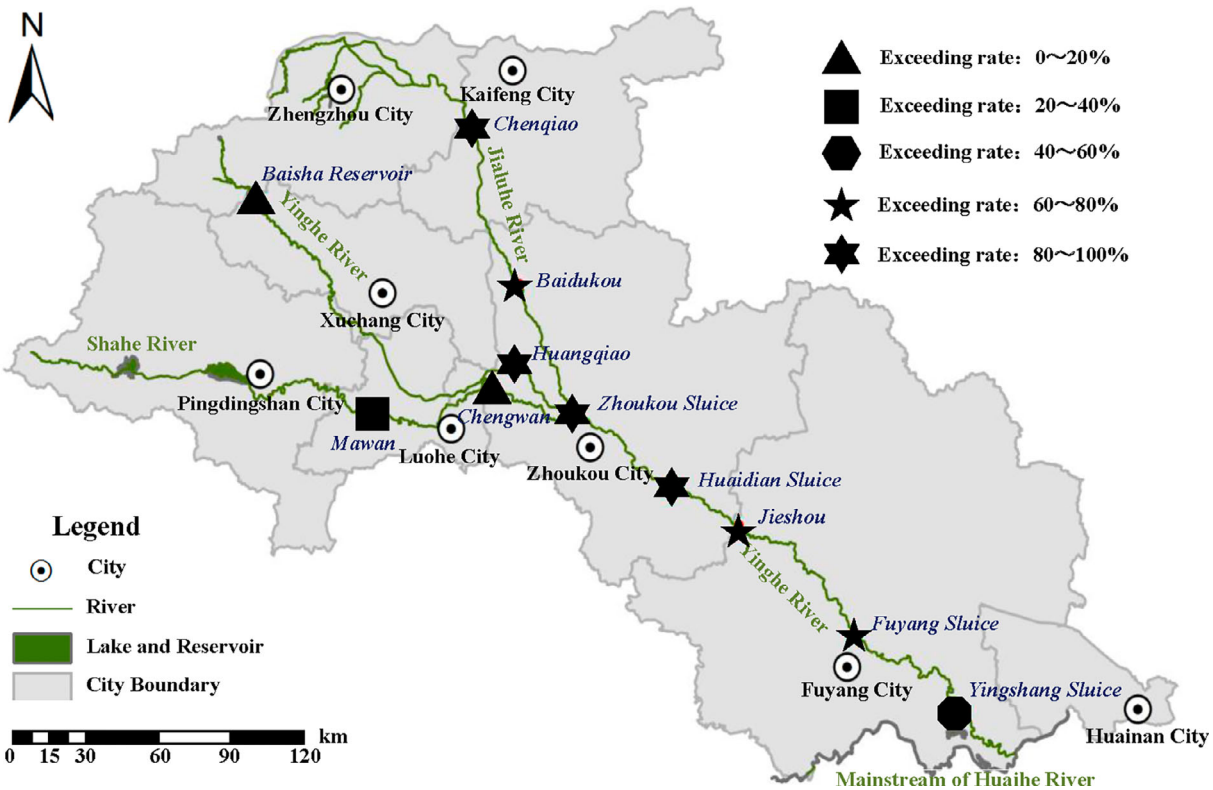

FIGURE 4 The spatial distribution of rate of exceeded standard water quality basing on the WPI in Shayinghe River Basin

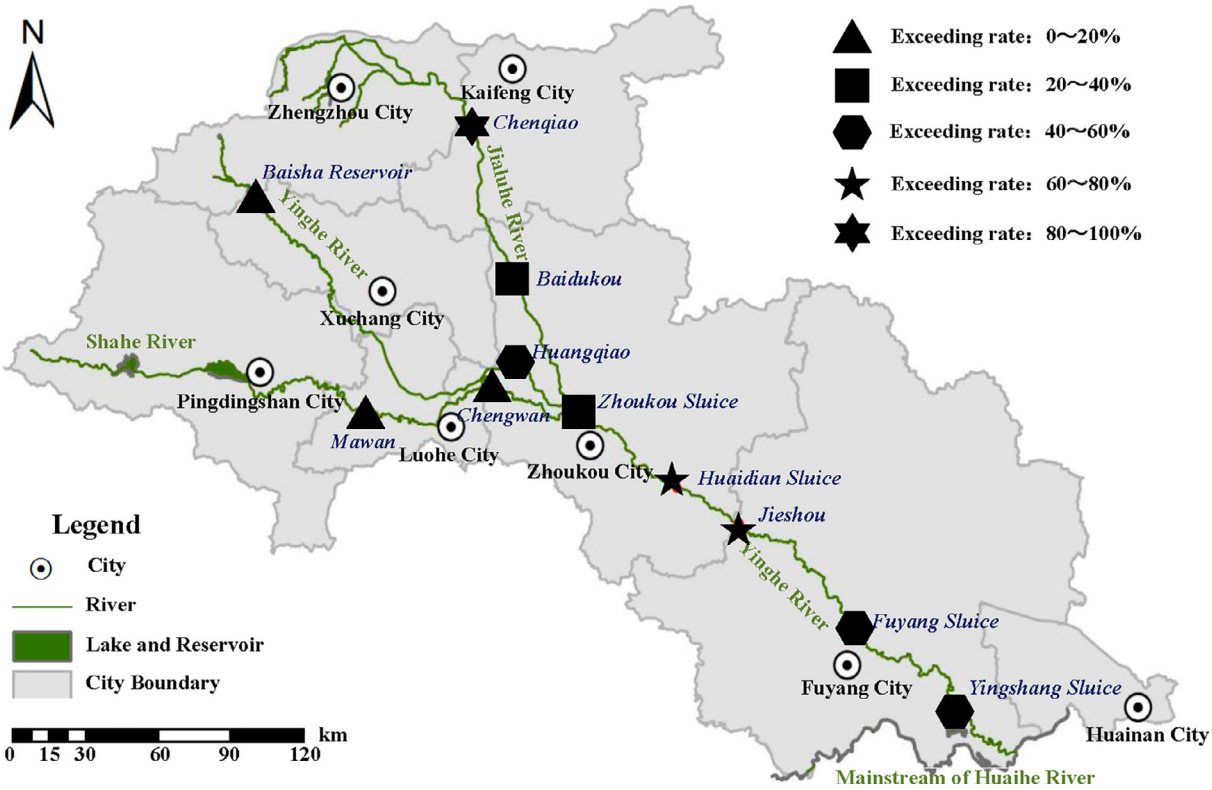

FIGURE 5 The spatial distribution of exceeding rates basing on the WPI in the hypothetical scenario in Shayinghe River Basin

exceeding rates are shown in Figure 5 based on the WPI in the hypothetical scenario in Shayinghe River Basin.

In Figure 5, the exceeding rates of WPI values were still found to be larger at Chenqiao and Huaidian Sluice and reached 95.37 and 72.32%, respectively, indicating that the impact of COD_{Mn} was still significant. The exceeding rates of WPI values showed a significantly decreasing trend at Baidukou, Mawan, Huangqiao, Zhoukou Sluice, Jieshou, Fuyang Sluice and Yingshang Sluice of 42.59, 23.15, 33.93, 58.04, 23.89, 30.36 and 29.46%, respectively. The water quality of these monitoring stations could be obviously improved by controlling the NH_3-N and TP.

3.3 | The variation trends of WPI for the monitoring stations

The time series of WPI values in the monitoring stations was analyzed according to the Mann-Kendall trend test, and the distributions of variation trends are shown in Figure 6. In Figure 6, the WPI values showed a slight upward trend at Baisha Reservoir, but the water quality was still in good; there were two obvious mutations at Baisha Reservoir in March 2013 and October 2014, when the WPI values reached 110.36 and 104.68, respectively. The WPI values showed a significant decreasing trend at Chenqiao, Baidukou, Huangqiao, Mawan, Chengwan, Zhoukou Sluice, Huaidian Sluice, Jieshou, Fuyang Sluice and Yingshang Sluice. There was an obvious mutation at Mawan in March 2013, and the WPI value reached 181.76; there were three obvious mutations at Chengwan in January 2011, March 2013 and October 2014, when the WPI values reached 123.70, 121.92 and 120.68, respectively, which might be due to a sudden water pollution incident during this period.

In summary, the water pollutants presented a significant decreasing trend in the Shayinghe River Basin, which indicated that the pollution control was relatively significant, which was consistent with the variation trends of the pollutant emissions in the Huaihe River Basin (Figure 7).

3.4 | The results of cluster analysis and box-plot analysis

The WPI values were analyzed by hierarchical clustering analysis, and the results of the temporal cluster analysis and spatial cluster analysis are shown in Figure 8.

In Figure 8a, the WPI values were divided into two major categories with respect to time: the first category was from January to June, and the second category was from July to December. The first category could be divided into two sub-categories: the first sub-category was from January to April, and the second sub-category was May and June; the second category also could be divided into two sub-categories, the first sub-category was from July to October, and the second sub-category was November and December. The results of temporal cluster analysis basically correspond to the flood season and non-flood season in the Shayinghe River Basin, which indicated that the water quality showed a significant difference in the flood season and non-flood season, but the water quality condition had no significant difference in each category. According to the comprehensive evaluation results of the water quality condition, the water

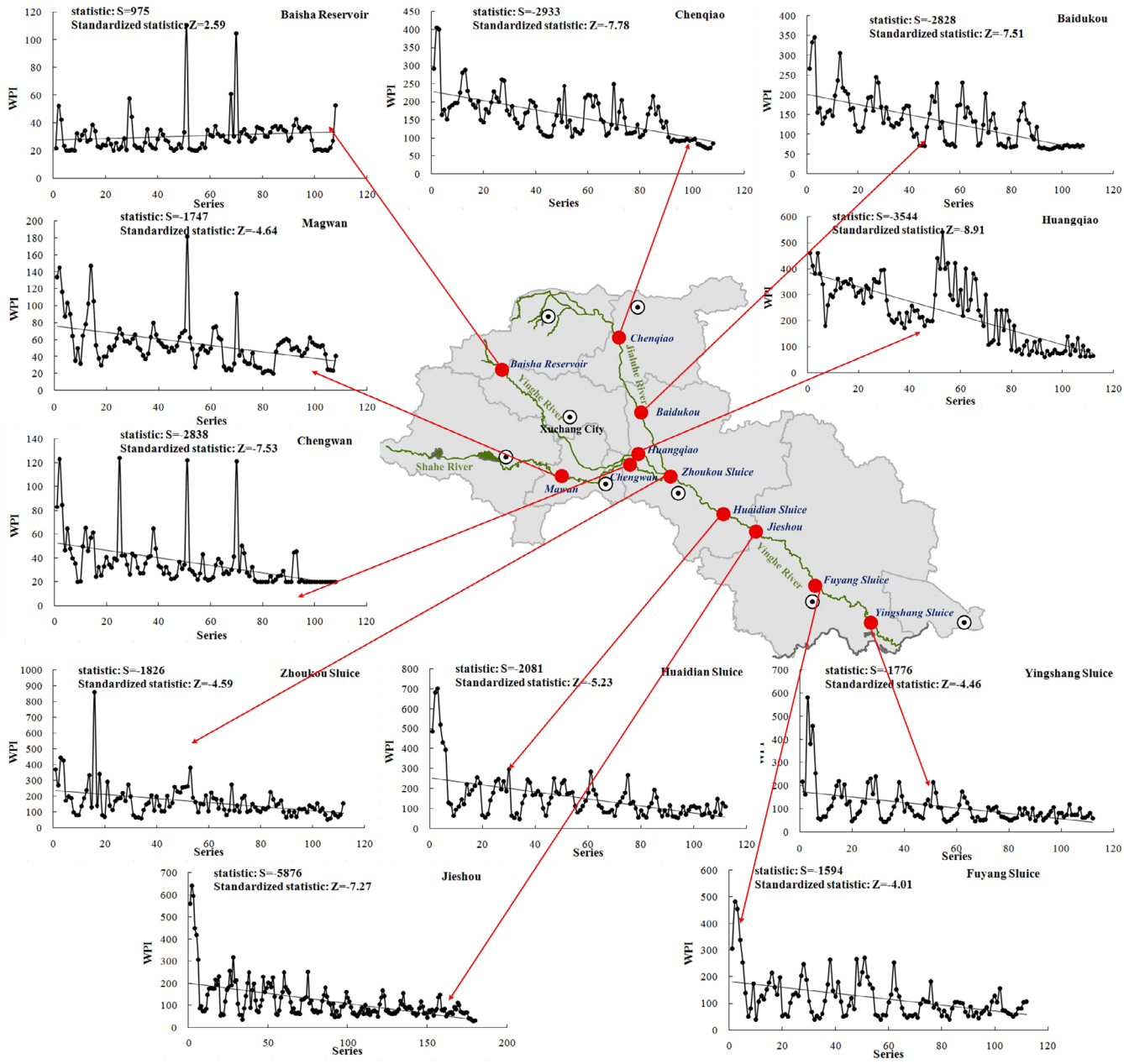

FIGURE 6 Results of the WPI for each monitoring station by Mann-Kendall trend analysis

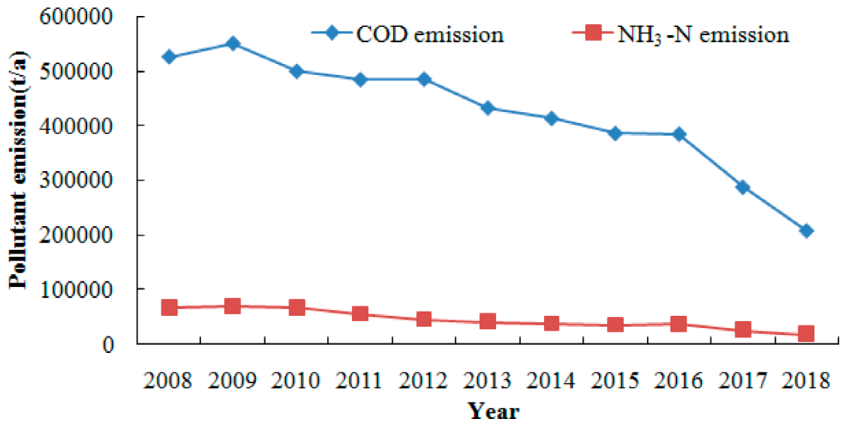

FIGURE 7 The variation trends of the pollutant emissions in Huaihe River Basin

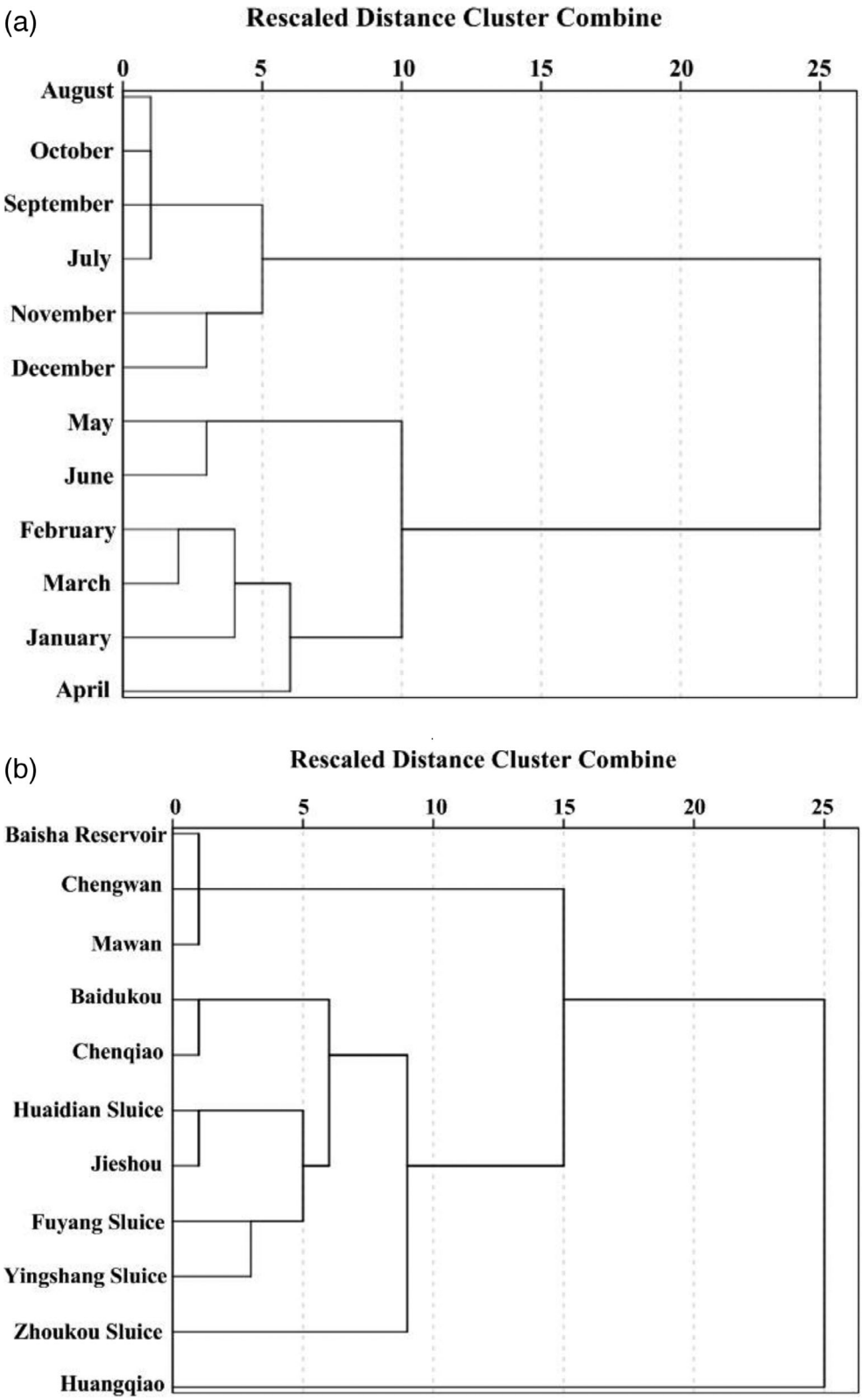

FIGURE 8 Dendrogram of temporal cluster analysis and spatial cluster analysis in Shayinghe River Basin (a) Results of temporal cluster analysis (b) Results of spatial cluster analysis

quality in the non-flood season was obviously inferior to that in the flood season in the Shayinghe River Basin, which should be used as a key period for water quality management and control.

In Figure 8b, the monitoring sections were spatially divided into three major categories, the first category included Baisha Reservoir, Chengwan and Mawan, where the water quality was the best; the second category included Chenqiao, Baidukou, Zhoukou Sluice, Huaidian Sluice, Jieshou, Fuyang Sluice and Yingshang Sluice; and the third category included Huangqiao, which was a monitoring station in which the Yinghe River flows into the Shayinghe River. The second category could

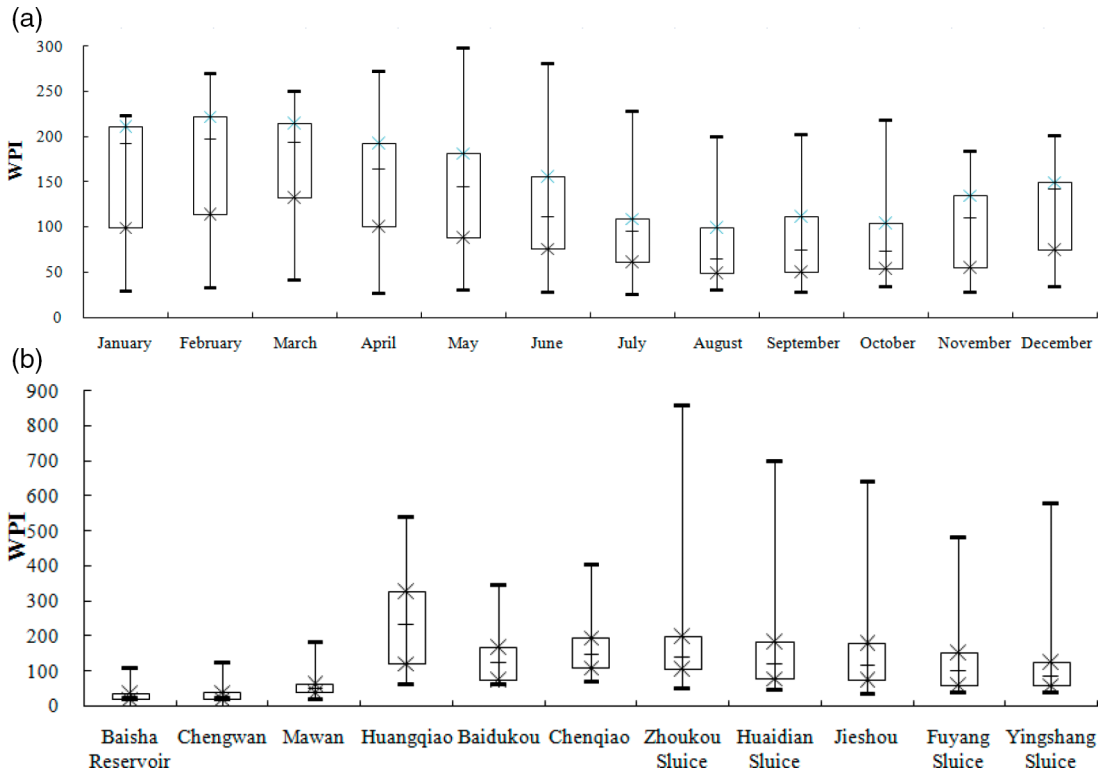

FIGURE 9 Results of the spatio-temporal distribution of the WPI by box-plot analysis. (a) Results of temporal box-plot analysis (b) Results of spatial box-plot analysis

be divided into two sub-categories: the first sub-category was Zhoukou Sluice, which is located at the intersection of Shahe River, Yinghe River and Jialuhe River. Here, the water quality situation reflected the water pollution condition in the upper reaches of Shayinghe River. The second sub-category included Chenqiao, Baidukou, Huaidian Sluice, Jieshou, Fuyang Sluice and Yingshang Sluice, and the spatial distribution of water quality was similar in this sub-category.

The results of the spatiotemporal distribution of the WPI values by Box-plot analysis are shown in Figure 9. In Figure 9a, the median of the WPI values presented a trend of decreasing first and then increasing. The variability of WPI values was relatively large in January to June, November, and December, and the variability of WPI values was relatively small in July to October. In Figure 9b, the WPI values had the greatest variability at Huangqiao, which indicated that the water quality condition changed considerably; the WPI values had relatively small variability at Baisha Reservoir, Mawan, and Chengwan, which indicated that the water quality conditions were relatively stable.

4 | DISCUSSION

4.1 | Sources analysis of pollutants in Shayinghe River

The sources of river water pollutants mainly included industrial wastewater, domestic sewage, livestock wastewater and agricultural non-point source pollution. Previous studies have analyzed the sources of pollutants in Wushui River Basin, Minjiang River Basin, Huangshui River Basin and Chishui River (Qiu et al., 2017; Tang et al., 2019; Teng et al., 2016; Zhu et al., 2018). The main influencing factors of water quality change were the discharge of industrial and agricultural wastewater, application of chemical fertilizers and pesticides, and operation condition of sluice in Shayinghe River Basin (Hu et al., 2018). There are many heavy polluting enterprises in the upper reaches of the Shayinghe River Basin, such as papermaking, brewing, chemical and pharmaceutical industries. A large amount of municipal domestic sewage is discharged with the increase of domestic water consumption; this sewage includes detergent sewage, household wastes and feces. The application of chemical fertilizers and pesticides is very large every year because the Shayinghe River Basin is an important commodity grain base in China. The exceeding rates of COD_{Mn}, NH_3-N and TP were higher in the Shayinghe River Basin, and the pollution of Jialuhe River was the most serious; Zhoukou Sluice is located at the intersection of Shahe River, Yinghe River and Jialuhe River, where the water quality was affected by the Jialuhe River.

According to the water resources bulletins of Huaihe River and Fuyang City, the discharge of industrial wastewater and domestic sewage, chemical oxygen demand and ammonium nitrogen reached 1,679 million tons, 140,100 tons and 14,200 tons, respectively, in Henan Province of the Huaihe River Basin in 2015. In addition, the discharge of industrial wastewater and domestic sewage, chemical oxygen demand and ammonium nitrogen reached 146.3 million tons, 10,080 tons and 1,676 tons, respectively, in Fuyang City in 2015. In recent years, the Chinese government has invested a large amount of financial

and material resources to prevent and control water pollution in the Shayinghe River Basin. The relevant measures include closing the heavy polluting enterprises, enhancing environmental legal enforcement and building sewage treatment plants, which was conducive to reduce the number of pollution sources and alleviate water pollution. Overall, the water pollution situation has improved in the Shayinghe River Basin.

4.2 | The influence analysis of runoff for water pollutants

The runoff exhibited the characteristics of the indeterminacy, intermittency, burstiness and uncontrollability, which posed a great threat to the river water environment (Li, Ren, et al., 2016). Runoff was the main non-point pollution source, accounting for 30% of the polluted water; and non-point source pollution accounted for 2/3 of the total pollution load (Han, Zhan, Lu, & &Wu, J., 2016; Hardy & Koontz, 2008). There was an extreme value of the runoff for the variations of NH_3-N and COD_{Mn} in the mainstream of Weihe River, such as the decline rate of NH_3-N and COD_{Mn} concentrations become significantly slower and stabilized when the runoff are greater than 250 m^3 s^{-1} and 350 m^3 s^{-1}, respectively (Wang, Sun, & Liu, 2011). The incidence of water pollution had an increasing trend under the influence of decreasing runoff coefficient in the Shaying River Basin, and the major impact areas were the Jialuhe River, the upper reaches of the Hongruhe River, and the Shayinghe River, such as due to the decrease of precipitation and runoff, the load of NH_3-N and COD_{Mn} in the near future at the outlet section decreased by 25.5–56.3% and 9.6–54.1%, respectively, in each month compared with the base year (Zhang, Hua, & Xia, 2017).

For the annual variation, the dilution effect of the water pollutants would be enhanced when the runoff was relatively large in the flood season in the Shayinghe River Basin, so the water quality condition in the flood season was better than that in the non-flood season. After the end of the flood season, the runoff would gradually decrease, and the sluices were beginning to store water when the flood season was coming to an end, which would reduce the discharged volume of the downstream in the Shayinghe River Basin, and the water quality of downstream would also be worsened with the reduction of runoff. The discharge of wastewater and sewage from the both sides of the Shayinghe River were accumulated in non-flood season, and the water quality would be worse with the increasing of sewage and storage time in the sluices. The water level sluice was adjusted to the flood limit water level before the flood season, which caused a large amount of sewage to be released in the downstream river. For the interannual variation, the runoff and WPI values presented an opposite trend, which showed that the water quality condition was better when the runoff increased and WPI values decreased, the water quality condition was poor when the runoff decreased and WPI values increased (Figure 10).

4.3 | The influence analysis of sluice regulation for water pollutants

The sluices and dams are water conservation projects that were built in a specific river reach and can control a certain area of the river basin, which is an important factor for human beings and can affect the natural shape of the river. Sluices and dams can raise the water level in the upstream river, regulate the flow in the downstream river, and change the flood runoff process, which can exert a functional effect on the water storage and flow regulation (Zhang, Xia, Liang, & Shao, 2010; Zhang, Xia, & Zhai, 2013). The flow velocity in front of the sluice would decrease because of the flow congestion when the sluice was closed or the opening of the sluice was small. A large quantity of water pollutants can be absorbed or deposited into the bottom sediment, which would enhance the bioaccumulation and weaken the aeration effect and self-purification ability of the water body. The scouring action of the water flow was strengthened for the sediment surface when the opening of sluice increased. The pollutants in the bottom sediment would return to the water body through resuspension and desorption, which would increase the pollutant content under the sluice, improve the self-purification ability of the water body and weaken the bioaccumulation; the simulated maximum values of TP concentration, TN concentration and PYT cell number are, respectively, 0.157 mg L^{-1}, 8.476 mg L^{-1} and 1,752.86 cell mL^{-1} in the upper section of the Huaidian Sluice when the opening of sluice is 30 cm, the simulated maximum values of TP concentration, TN

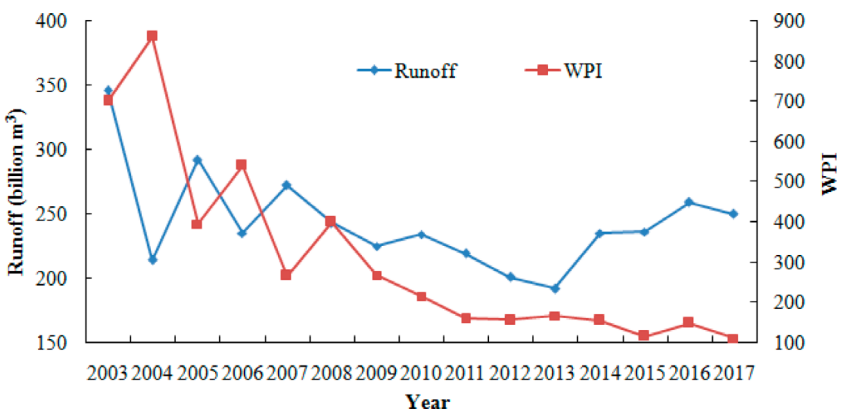

FIGURE 10 The variation trends of runoff and WPI values

concentration and PYT cell number are, respectively, 0.175 mg L^{-1}, 8.589 mg L^{-1} and 2,271.18 cell mL^{-1} in the upper section of the Huaidian Sluice when the opening of sluice is 80 cm (Dou, Mi, Li, & Zhang, 2016; Dou, Mi, & Zuo, 2015). Zhoukou Sluice, Huaidian Sluice, Fuyang Sluice and Yingshang Sluice are the main sluices in the Shayinghe River Basin. Sluice regulation had a certain effect on the migration and transformation of pollutants. The spatiotemporal distribution of water pollutants was changed through the reasonable sluice regulation, adjustment of water level in front of the sluice and control of discharge flow under sluice, which could reduce the occurrence of sudden water pollution accidents (Li & Zuo, 2012). Yingshang Sluice is the last control sluice before the Shayinghe River flows into the Huaihe River. The discharge flow of the Yingshang Sluice was reasonably adjusted, and the water environmental capacity of the mainstream of the Huaihe River was fully utilized, which reduced the accumulated sewage in the Shayinghe River and avoided the pollution accidents of the mainstream of the Huaihe River caused by concentrated discharge of sewage (Zhao, Li, & Zuo, 2012).

Overall, water pollution control measures should be proposed to improve the water quality according to the causes of pollution in different periods and river sections after analyzing the water environmental pollution in the river. There are many sluices in the Shayinghe River Basin. The joint prevention of water pollution and combined dispatch of sluices has become an important means to solve the water pollution problem.

5 | CONCLUSIONS

Using water quality monitoring data from 11 monitoring stations in the Shayinghe River Basin, this study analyzed the spatiotemporal distribution characteristics and sources identification of water pollutants. Some concluding remarks from this research are as follows: (a) The water quality standard of classes mainly belonged to Class IV or above in the Shayinghe River Basin, accounting for about 70%, but the water quality standard of classes reached Class I and Class II for less than 15%. The water quality in non-flood season was obviously inferior to that in the flood season, the TP was the key control index in the flood season, and the NH_3-N was the key control index in the non-flood season. (a) The exceeding rates of WPI values exceeded 80% at Chenqiao, Huangqiao, Zhoukou Sluice, Huaidian Sluice and Jieshou. The WPI values showed obvious mutations in January 2011, March 2013 and October 2014 at Baisha Reservoir, Mawan and Chengwan. The exceeding rates of WPI values showed a significantly decreasing trend at Baidukou, Mawan, Huangqiao, Zhoukou Sluice, Jieshou, Fuyang Sluice and Yingshang Sluice in the hypothetical scenarios. (3) The WPI values were divided into two major categories with respect to time, and the water quality condition had no significant difference in the each category. The non-flood season should be used as a key period for the water quality management and control. The variability of WPI values was relatively large in the January to June, November and December, and the variability of WPI values was relatively small in the July to October. (4) The monitoring sections were spatially divided into three major categories, the spatial distribution of water quality was similar in the categories. The WPI values had the greatest variability at Huangqiao, and the WPI values had relatively small variability at Baisha Reservoir, Mawan and Chengwan.

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DATA AVAILABILITY STATEMENT

The acquisition of datasets has been introduced in "Materials and methods" and is available from the corresponding author on reasonable request.

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