Assessment and Spatiotemporal Variation Analysis of Water Quality in the Zhangweinan River Basin, China

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Abstract

Spatiotemporal variation analysis of water quality and identification of water pollution sources in river basins is very important for water resources protection and sustainable utilization. In this study, fuzzy comprehensive analysis and two statistical methods including cluster analysis and seasonal Kendall test method were used to evaluate the spatiotemporal variation of water quality in the Zhangweinan River basin. The results for spatial cluster analysis and assessment on water quality at 19 monitoring sites indicated that water quality in the Zhangweinan River basin could be classified into two regions according to pollution levels. One is the Zhang River basin located in northwest of the Zhangweinan River basin where water quality is good. Another one includes the Wei River and eastern plain of the Zhangweinan River basin, and the water pollution in this region is serious, where the pollutants from point sources flow into the river and the water quality changes greatly. The results of temporal cluster analysis and seasonal Kendall test indicated that the sampling periods may be classified into three periods during 2002-2009 according to water quality. Results of temporal cluster analysis and seasonal Kendall test indicated that the study periods may be classified into three periods and two different trends was detected during the period of 2002-2009. The first period was the year of 2002-2003, during which water quality had deteriorated and serious pollution was observed in the Wei River basin and eastern plain of the Zhangweinan River basin. The second period was the year of 2004-2006, during which water quality became better. The year of 2007-2009 is the third period, during which water quality had been improved greatly. Despite that water quality in the Zhangweinan River basin had been improved during the period of 2004-2009, water quality in the Wei River (southwestern part of the basin), the Wei Canal River and the Zhangweixin River (eastern plain of the basin) is still poor. These results provide may useful information for better pollution control strategies in the Zhangweinan River basin.

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Keywords: Zhangweinan River; water quality; fuzzy comprehensive assessment; multivariate statistical analysis

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1. Introduction

Water quality in rivers is an important problem for water environment management. The spatial-temporal distribution of water quality could provide dynamic information for the decision maker of water environment management [1]. It is necessary to properly evaluate the spatial and temporal pattern of water quality in rivers, which is influenced by multiple-factors. There are a large amount of complicated phenomenon and multiple-factor in comprehensive water quality evaluation, and many fuzzy phenomenon and concepts are involved in the evaluation [2]. The variation of water quality was recognized as a continuous process. The fuzzy comprehensive analysis is able to catch this characteristics and the analysis results is more reasonable and close to real situation[3], thus fuzzy comprehensive analysis is widely applied in water quality evaluation of surface water body, such as rivers [3-7], reservoirs [8] and lakes [2,9]. So far, the major technique for investigating the spatial pattern of water quality is multivariate statistical analysis [10], which is an important tool to study spatial-temporal pattern of water quality [11]. It was applied in Jinshui River [11,12], Xiangxi River [1], Du River [13], upstream of Hanjiang River [14], and Xiangjiang River [15] in China. It was also applied in other rivers in foreign countries, for example, Pisuerga River in Spain [16], the estuary of Malaysia [17], Fuji River in Japan [18], Behrimaz River in Turkey [19], Bagmati River in Nepal [20], Ganga River [21], Mahanadi River [22], Gomti River [23], Brahmani River in India’s [24], Suquia River in Argentina [25] and Nakdong River in Korea’s [26].

At present, most of researches in the Zhangweinan River basin focused on water resources management [27,28], water pollution control [29], water ecology restoration [30], heavy metal pollution and ecological risk evaluation [31]. There were fewer researches on water quality evaluation and spatial-temporal variation, which is extremely necessary to river basin management. In this study, fuzzy comprehensive analysis and multivariate statistical analysis were applied to evaluate the river water quality and to analyze the spatial-temporal variation of water quality in the Zhangweinan River basin. The conclusions could provide scientific evidence for water environment management.

2. Materials and methods

2.1. Study area description

Zhangweinan Canal water system is located in east of Taiyue Mountain, south of Fuyang River and Ziyang River and north of Yellow River and Majia River. The catchment lies in 112-118°E, 35-39°N and comprise of Zhang River, Wei River, Wei Canal, Zhangweixin River and Nan River, running cross Shanxi, Henna, Hebei and Shandong provinces and finally entering Bohai Sea. The area of catchment is 37700 km², in which mountainous area is about 25466 km², accounting for 68% and plain area is 12234 km² accounting for 32% (Fig.1). The meteorological condition of the catchment is temperate semi-arid, semi-humid monsoon climate with a 14°C of average annual temperature. The general geographic characteristic of the catchment is the southwest higher than the northeast with an average slope of 0.263%. Runoff generated in the catchment originates from two major tributaries Zhang River and Wei River. The average annual precipitation is 604mm overall the river basin with 584mm in Zhang River basin, 652mm in Wei River basin, 567mm in mid-downstream area. The maximum annual precipitation was 997mm (1963) and minimum one was 339mm (1965). Most of annual precipitation takes places in flood seasons (6-9 month) with 448mm of precipitation accounting for 74% of the annual precipitation.

2.2. Study methods description
2.2.1. Fuzzy mathematics

Fuzzy comprehensive analysis, based on fuzzy mathematics to quantify factors with unclear boundary or difficult to quantify, is a method to comprehensively evaluate water quality [2]. The detailed mathematical description could be found in literatures [7].

2.2.2. System cluster analysis

System cluster analysis is a widely used cluster analysis method, involving variable cluster and sample cluster. The core concept is to regard each individual as one cluster and combine two clusters with highest similarity as a new cluster, then combine this new cluster with another most similar cluster as another new cluster. This process is repeated over and over again until all clusters become one cluster. In water quality evaluation in rivers, cluster analysis is usually based on geographic location of monitoring date and location.

2.2.3. Seasonal Mann - Kendall

It is improper to compare water quality data between flood season and non-flood season, as the river water quality was influenced by the change of river flow. In order to avoid seasonal influence, water quality data should be analyzed in the same month over years. Seasonal Kendall test could be applied when time series has missing data and abnormal distribution variables. The idea of this method is to separately calculate the test statistics and variance of water quality data in each season and then overall statistics was calculated. The significant trend test was identified by comparing overall statistics with standard normal distribution. The seasonal Mann–Kendall method has been useful for nonparametric trend analysis of water quality [32-39]. The detailed mathematical description could be found in literatures [33].

2.3. Data pretreatment

Water quality data in the Zhangweinan River basin from 2001 to 2009 is provided from Zhangweinan River Administration, Ministry of Water Resources. Monitoring sites include Liujiazhuang (Zhang River), Kuangmenkou (Zhang River), Tianqiaoduan (Zhang River), Guantai (Zhang River), Yuechengshuiku (Zhang River), Qimen (Wei River), Xiaohetiao (Wei River), Yangzhuangqiao (Wei River), Wuling (Wei River), Longwangmiao (Wei River), Baizhuangqiao (Wei Canal), Beiguanzao (Wei Canal), Xianfengqiao (Wei Canal), Sinvsizha (Wei Canal), Disandian (Nan Canal), Wuqiaozha (Cha River), Yuanqiaozha (Jian River), Wangyingpan (Zhangweixin River), and Xinjizha (Zhangweixin River), 19 monitoring sections could be found in Figure 1. Water quality factors include electrical conductivity (EC), dissolved oxygen (DO), potassium permanganate index (CODMn), 5-day biochemical oxygen demand (BOD5), total hardness (TH), total suspended solids (TSS), Chloride (Cl), Sulphate (SO4^2-), Total nitrogen (TN), ammonia nitrogen (NH4^+-N), Nitrate nitrogen (NO3^--N), total phosphorus (TP), fluoride (F), volatile phenol (V-ArOH), total cyanide (T-CN^-), total mercury (THg), Arsenic (As), chromium with a valence of six (CrVI). Referring to surface water quality standard (GB3838-2002), DO, CODMn, BOD5, NH4^+-N, NO3^--N, F-, V-ArOH, T-CN^-, THg, As, and CrVI were selected as the indicators to evaluate water quality by using fuzzy comprehensive analysis and spatial-temporal variation of water quality from 2001 to 2009. Water quality was also analyzed during flood and non-flood seasons.
3. Results analysis

3.1. Water quality evaluation

Results of water quality evaluation by using fuzzy comprehensive analysis are shown in Table 1. Overall water quality in the Zhanghe River is fine and the water quality in non-flood season is better than that in flood season. Among all sections, water quality in 5 sections during non-flood season reach class I of GB3838-2002 standard while classes II and III appear during flood season. Class V of water quality once took place in Guantai section during flood season in 2001. The water quality in 14 sections located in Wei River, Wei Canal, Nan Canal, Cha River, Jian River and Zhangweixin River are all in class V. More serious pollution in the main river could be related to the accumulative effect of pollutants.

3.2. Cluster analysis

3.2.1. Time clustering analysis

From the results of time cluster analysis, the water quality in flood seasons from 2001 to 2009 could be divided into three periods. The first period is from 2002 to 2003 with extremely heavy pollution. The second period is from 2004 to 2006 with heavy pollution but better than period stage. COD and BOD$_5$ declined significantly but still greatly exceed the standard. The third period includes 2001, and from 2007...
to 2009 with less heavy pollution. The water quality in this period was improved further compared to second period. COD and BOD₅ in 2007 to 2009 became much better and the water quality was improved greatly (Fig. 2). The water quality in Yuecheng Reservoir satisfies the standard of class I and II according to the surface water quality standard (GB3838-2002).

In non-flood season, the water quality variation could be divided into four periods; four periods are divided into two kinds of trends. In the first period, 2001 and second period, from 2002 to 2003, water quality was become worse. The second period, from 2002 to 2003, was regarded as extremely heavy pollution period. In the third period, from 2004 to 2005, and the fourth period, from 2006 to 2009, the pollution mitigated to some extent. COD and BOD₅ declined significantly but still greatly exceed the standard. During the fourth period, water quality would show a significant improvement every two years (Figure 2) and had been keeping improving. Yuecheng Reservoir satisfies the standard of Class I according to the surface water quality standard (GB3838-2002).

![Fig. 2 Dendrogram of sampling periods based on cluster analysis](image-url)

3.2.2. Spatial clustering analysis

From results of spatial cluster analysis, the water quality could be divided into five levels (Fig. 3), level I (average), level II (slightly severe), level III (severe), level IV (very severe), level V (extremely severe). In the flood season, water quality at Wuqiaozha section is in level V, Disandian section in Nan Canal in level IV, Xinjizha section in the Zhangweixin River in level III, and sections of Baiqiaohe, Qimen, Xiaohetiao, Yangzhuangqiao, Wuling, Longwangmiao, Beiguantao, Xianfengqiao and Sinvshizha in the Wei Canal and sections of Wangpanying and Xinjizha are all in IV. Sections of Liujiashuang, Kuangmenkou, Tianqiaoduan, Guantai and Yuecheng Reservoir are in better condition with a level I. Xinjizha section, the estuary of river basin, is polluted heavily. Water quality monitoring data shows that electrical conductivity, total hardness, Chloride (Cl⁻), Sulphate are much higher than that in other sections. The reason may be that the Xinjizha section is usually in closed state during non-flood seasons and only discharge flood in flood seasons.

In non-flood seasons, water quality could be divided into four levels. The definition of four levels is similar to that in flood seasons: level I (average), level II (slightly severe), level III (very severe), and level IV (extremely severe). The Disandian section in Nan Canal is in level III, sections of Baizhuangqiao, Qimen, Xiaohetiao, Yangzhuangqiao, Wuling, Longwangmiao, Beiguantao, Baizhuangqiao, Xianfengqiao, Sinvshizha in the Wei River, Xuanqiaozha section in the Jian River and sections of Wangpanying and Xinjizha in the Zhangweixin River are in level II, sections of Liujiashuang, Kuanmenkou, Tianqiaoduan, Guantai and Yuecheng Reservoir in the Zhang River in level I. According to
the results of cluster analysis and the surface water environment quality standard, the water quality condition in the study area showed an obvious spatial distribution that upstream of the Zhang River in northwestern basin is one group and the Wei River basin and eastern plain area is another group, in those areas water were severely polluted due to the industrial waste water and sewage discharge.
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| non-flood season |      |              |             |             |         |               |       |            |                |        |               |             |         |              |          |          |        |         |            |          |
| 2001         | I    | I            | I           | I           | I       | V             | V     | V          | V               | V      | V             | V           | V       | V             | V        | V        | V       | V       | V          | V        |
| 2002         | I    | I            | I           | I           | I       | V             | V     | V          | V               | V      | V             | V           | V       | V             | V        | V        | V       | V       | V          | V        |
| 2003         | I    | I            | I           | I           | I       | V             | V     | V          | V               | V      | V             | V           | V       | V             | V        | V        | V       | V       | V          | V        |
| 2004         | I    | I            | I           | I           | I       | V             | V     | V          | V               | V      | V             | V           | V       | V             | V        | V        | V       | V       | V          | V        |
| 2005         | I    | I            | I           | I           | I       | V             | V     | V          | V               | V      | V             | V           | V       | V             | V        | V        | V       | V       | V          | V        |
| 2006         | I    | I            | I           | I           | I       | V             | V     | V          | V               | V      | V             | V           | V       | V             | V        | V        | V       | V       | V          | V        |
| 2007         | I    | I            | I           | I           | I       | V             | V     | V          | V               | V      | V             | V           | V       | V             | V        | V        | V       | V       | V          | V        |
| 2008         | I    | I            | I           | I           | I       | V             | V     | V          | V               | V      | V             | V           | V       | V             | V        | V        | V       | V       | V          | V        |
| 2009         | I    | I            | I           | I           | I       | V             | V     | V          | V               | V      | V             | V           | V       | V             | V        | V        | V       | V       | V          | V        |
3.3. Seasonal Mann–Kendall trend analysis

Relative long-term water quality monitoring has been done reliable data series were chosen to determine the factors for trend analysis. In this section, trend for the concentration of COD$_{Mn}$, NH$_4^+$-N, TN, TP, F$^-$, V-ArOH, Cr$^{6+}$, Hg, As and T-CN was detected.

Table 2 Trend test results of water quality in the Zhangweinan River basin

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<th>River</th>
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<th>BOD$_5$</th>
<th>COD$_{Hb}$</th>
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Fig. 3 Dendrogram of sampling sites based on cluster analysis
From Table 2, it can be seen that water quality at most of the sections becomes better. For example, volatile phenol significantly declined in Liujiazhuang, Kuangmenkou and Guantai sections and TN in Yuecheng Reservoir drop ed greatly. In these four sections, other indicators do not show obvious change. It indicated that the water quality is in a relatively good condition (Table 1). However, CODMn, TN, TP and volatile phenol at Tianqiao section in the Zhuozhang River show great increasing trend, which should be paid attention. At sections of Xiaqiaohu, Yangzhuanqiao in the Wei River and sections of Beiguanqiao, Xianfengqiao, Baihuangqiao and Sinshizha in the Wei Canal, aerobic index (BOD5, CODCr), nutritional index (NH4+-N, TN, TP), F- and volatile phenol decreased to different extent. It indicated that water quality becomes better. However, at Qimen section in middle and upper stream of the river basin, all water quality indicators fail to show obvious change and evaluation of water quality is poor. thus show that the water pollution control above the Qimen section has a long way to go. BOD5, CODCr, NH4+-N, TN decreased in sections of Disandian, Wuqiaoza, Yuanqiaoza, Wangyingpan and Xinjizha. Attention should be paid to sections of Wuqiaoza and Disandian, where TP has a tendency of increasing. Much attention should be paid to Yuanqiaoza, Wuqiaoza, Wangyingpan and Xinjizha, where volatile phenol shows a significant climbing trend. The change of Cr6+, Hg, As and total cyanide are not significant in 19 monitoring sections. It is partly because the concentration of these four indicators in river is relatively low and it could be related to the fact that heavy metals are prone to deposit in sediments. In general, water quality in the Zhangweinan River basin shows a great improvement. It should be resulted from the scientific management and strict enforcement during the past years.

4. Discussion

Water quality in the Zhangweinan River basin shoulded a significant pattern of spatial variation. From results of cluster analysis, the whole basin has experienced a period of pollution worsening (2002-2003) and mitigation period (2004 - 2009). Kendall trend test also confirmed that the water quality has become better. In 2004, many factories with the production line of lime-base process pulping with annual production capacity under twenty thousand tons, and alkali straw pulping under seventeen thousand tons have been closed. therefore, the COD dropped greatly. Meanwhile, Henan Province has invested to build several sewage treatment plants to further reduce the COD discharge.

Water quality could be divided into two regions in spatial pattern. One is the Zhang River basin in northwest where water quality is better, and the other is the Wei River basin in south, Wei Canal, Nan Canal and Zhangweixin River basin in eastern plain, where the water quality is poor without basic water function. In the Wei River basin, Wei Canal, Nan Canal and Zhangweixin River basin, water quality could be divided into four periods in flood seasons and three periods in non-flood seasons. In upstream of the Yuecheng Reservoir in the Zhang River basin there is few hydraulic engineering projects, natural flow is relatively large and amount of sewage outlets is less compared with the Wei River and east plain. While the natural flow is smaller in southern part of the Zhangweinan Canal and east plain, there is no natural flow in the channel in most time of the year. In upper stream of the Wei River, coal chemical industry,
Steel, coal mining and paper industry are highly concentrated in cities including Jiaozuo, Xinxiang and Anyang, therefore, total pollution emission, COD and NH$_4^+$-N emission accounts for more than 65% of the whole emission in the study area, Wei River, therefore, was highly contaminated. The polluted water in the Wei River runs into the Wei Canal through Sinviszha after confluence with the Zhang River. Water quality was improved to some extent as the result of self-purification process along the channel, but large amount of sewage is discharged into the channel at Linqing city in Shandong Province, which further results in the deterioration of water quality. Nan Canal receives part of industrial waste water and sewage discharged at Dezhou, Shandong Province, which causes the deterioration of water quality at Disandian section. Cha River also receives industrial waster water from Dezhou, and resulting in further drop of water quality. However, water quality in the Jian River, which does not receive sewage, is much better than that in the Nan Canal and Cha River. Cha River and Jian River converge into the Zhangweixin River, which receives part of industrial waste water, and result in the deterioration of water quality at Wangpanying and Xinjizha sections. In addition to large amount of industrial waste water and sewage discharged, storage of reservoirs resulted in the decrease of streamflow and been dry-up in downstream. The artificial regulation of natural runoff by a large number of water control projects in the Wei Canal, Nan Canal, Cha River, Jian River and Zhangweixin River is one of reasons that water quality in the Zhangweinan River basin shows a discrepant spatial distribution. The regulation of water control projects in the river basin directly influences the streamflow in the river, further influences water environment capacity of the river, and further affects the water quality. For example, the regulation of water control projects at Sinvyszha directly influences the streamflow in the downstream of Nan Canal, Cha River and Jian River, and further affects water quality downstream.

Fig 4 Sewage constitute in the Zhangweinan River basin                         Fig 5 Total amount of emissions, COD and NH$_4^+$ load

5. Conclusions

(1) Water quality in the Zhangweinan River basin could be divided into two regions in space according to pollution levels. One is the Zhang River basin in northwest of the Zhangweinan River basin where water quality is good. Another one includes the Wei River and eastern plain of the Zhangweinan River basin, and the water pollution in this region is serious.

(2) Flood seasons in the Zhangweinan River basin from 2001 to 2009 could be divided into three periods. The first period is from 2002 to 2003 with extremely heavy pollution. The second period is from 2004 to 2006 with heavy pollution but better than first period. The third period is from 2007 to 2009. Water quality in this period was further improved compared to second period. This is also confirmed with the results of seasonal Kendall test.
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