

Temporal and spatial characteristics of surface water quality by an improved universal pollution index in red soil hilly region of South China: a case study in Liuyanghe River watershed

Zhongwu Li · Yong Fang · Guangming Zeng ·
Jianbing Li · Qi Zhang · Qingshui Yuan ·
Yamei Wang · Fangyi Ye

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Abstract Selecting the Liuyanghe River watershed as an example, using monitoring data of water quality of nearly 10 years and the improved synthesis pollution index method to evaluate the water quality, the research studied the temporal and spatial characteristics of surface water quality of a typical basin in the red soil hilly region, and analyzed reasons for the surface water quality change. The results indicated the improved synthesis pollution index had a better serviceability than other methods, such as, Pollution Index method, Fuzzy Evaluation method, Grey-System method etc. As for the temporal characteristic, because of no-point source pollution, the water quality of Liuyanghe River watershed had become a more and more serious problem over a ten-year period. The spatial characteristic indicated that the pollution degree increased from upstream to downriver. Water quality upstream was better, and the content of the heavy metals was higher in the middle of the river, and the pollution of ammonia nitrogen intensified downriver. The result suggested the improved universal pollution index could be used in the assessment of the water environment.

Keywords Red soil hilly region · Surface water · Evaluation of water quality · Pollution index

Introduction

Appropriate water quality assessment is very important for water resource universal utilization in watershed scale. At the present time, there are many methods to assess watershed water quality, such as Pollution Index method (Nives 1999; Pesce and Wunderlin 2000), Fuzzy Evaluation method (Chang et al. 2001; Lu and Lo 2002; Liou et al. 2005; Zou et al. 2006), Matter-Element Model method (Zhang and Liang 2005), Neural Network method (Shetty et al. 2003; Chaves and Kojiri 2007; He and He 2008), seasonal Kendall examination method (Hirsch 1982) and Grey-System method (Karmakar and Mujumdar 2006, 2007). All methods have some advantages and disadvantages for assessing water quality in river systems. The fuzzy evaluation method, matter-element model method, neural network method, and grey-system method can be logically combined with national standards to evaluate water quality grade, but its calculation is very complicated, and it can not compare with the same grade water quality. The seasonal Kendall examination method can easily exclude interference of synthetic factors, but it needs much more data, and it can only judge general change trend. Although the pollution index method can be easily used, it is not convenient to compare with national water quality standards because pollution degrees are divided into several grades factitiously. Thus, an improved universal pollution index method (IUPI method) emerged, whose aim was to assess the water quality and judge the water pollution degradation in a simple and easy way (Xu 2005a). Xu (2005b) used this method to assess the water quality of

Z. Li (✉) · Y. Fang · G. Zeng · J. Li · Q. Zhang ·
Q. Yuan · Y. Wang · F. Ye
College of Environmental Science and Engineering,
Hunan University, Changsha 410082,
People's Republic of China
e-mail: lizhongwu@yahoo.com.cn

J. Li
Environmental Engineering Program,
University of Northern British Columbia,
Prince George, BC V2N 4Z9, Canada

the rivers in Shanghai, and obtained a reasonable result. However, equal weight for different parameters is a limitation of the method. As a result, in this paper, the IUPI method, integrated with an excess standard rate (The “excess standard rate” means probability of concentration of pollutant in all profiles is higher than the National Standard for relevant water quality types) method, which was used to get weights of each parameter, was selected to assess water environment quality.

The red soil hilly region is of low ecological stability and high fluctuation in biological systems and productivity, sensitive to the activities of humans, and sudden disasters. The physical environment always tends to be more and more deteriorative, and difficult for human being’s survival (Cao et al. 1995). The distribution of red soil hilly regions in South China is broad, including 11 provinces and 619 counties in southern China, occupying an area of 1.13 million km² and accounting for 11% of the total area of China (Lu and Shi 2000). Here, the subtropical monsoon climate gives the region sound bioclimatic conditions (annual rainfall of 1,400–1,700 mm, mean annual temperature of 16–19°C) and a strong potential for producing enormous quantities of biomass. Due to the long-term excess exploitation of natural resources, the red soil hilly region has become one of the most vulnerable eco-environment regions in China (Cao et al. 1995), characterized by serious soil erosion, heavy floods and droughts, degressive land productivity, and degraded ecological stability; even in some areas, a landscape similar to a desert (named red desertification) is emerging (Tian et al. 2001). Meanwhile, the serious soil erosion will also cause some changes in water quality.

The objectives of this study are expected to disclose the temporal and spatial variations of water quality in red soil hilly regions, and to find a good approach to universally assess the water environment quality.

Study site

In the research, a typical watershed—Liuyanghe River watershed of Red Soil Hilly Region was selected as the study site. Liuyanghe River, a tributary of Xiangjiang River, locates in East part of Hunan Province, China, spanning over 112°58′–114°15′E and 27°51′–28°34′N (Fig. 1). Liuyanghe River, originating from North part (Hengshanao) of Dawei Mountain of Luoxiao Mountain Range, has two branches: Daxi River and Xiaoxi River. It passes through Liuyang City, Changsha County and Changsha City district, and drains into Xiangjiang River, which has a length and an area of 235 km and 3,922 km² respectively. As a typical red soil hilly region, the area of red soil contributes 52% of total area, and the soil organic matter content is abundant, achieving 2 ~ 3%. The

hypography properties in Liuyanghe River watershed are high in East part and low in West Part, of which the highest altitude is about 1,607 m in Qixing Mountain. The Liuyanghe River altogether has nine hydrological monitoring profiles from headwaters, including Xiaoxi, Daxi, Liuyang City Center, 3rd waterworks, Zhaba, Zhangshuchong, Langli, Heishi ferry, Delta (Fig. 1). Because of more and more serious water pollution (including heavy metal pollution and industrial wastewater) in the Xiangjiang River, the Changsha City government had decided to search for new water resources. The Zhushuqiao Reservoir in the upstream of Liuyanghe River is selected as the water supply field for drinking. In Jan. 2006, the Chinese government authorized the establishment of the Clean Drinking Water Project, which involved transferring water from Zhushuqiao Reservoir to Changsha City district. The project made the prevention of water pollution in the Liuyanghe River watershed more and more important, and become one of the main restricting factors affecting the construction of Changsha City and the protection of its eco-environment protecting. As a result, research on temporal and spatial variations of water quality in Liuyanghe River watershed has become essential.

Methods and process

Assessment method of water quality

In research, an Improved Universal Pollution Index (IUPI) method was adopted. The steps of this method are illustrated below.

Single factor index calculation of each profile

The single factor indexes (P_i) of each profile in Liuyanghe River were calculated by single factor water quality index method, which was put forward by Xu (2005a). P_i consists of integer and decimal fraction. Pollution grade can be judged by integer and the difference of pollution degree in same grade can be judged by decimal fraction. The P_i can be expressed by the following formula:

$$P_i = X_1 \times X_2 \quad (1)$$

where X_1 was the inter, and showed the type of water quality index; X_2 was the decimal fraction, and showed the degree of monitoring data in interval of X_1 type water quality changing. For instance, if the concentration of COD is 28 mg/L, according to the national standards, it belongs to the water type IV (20–30 mg/L), so $X_1 = 4$; and $X_2 = \frac{\text{COD}_{\text{Mn}} - 20}{30 - 20} = 0.8$. The detailed method of X_1 , X_2 can be seen in Xu (2005a).

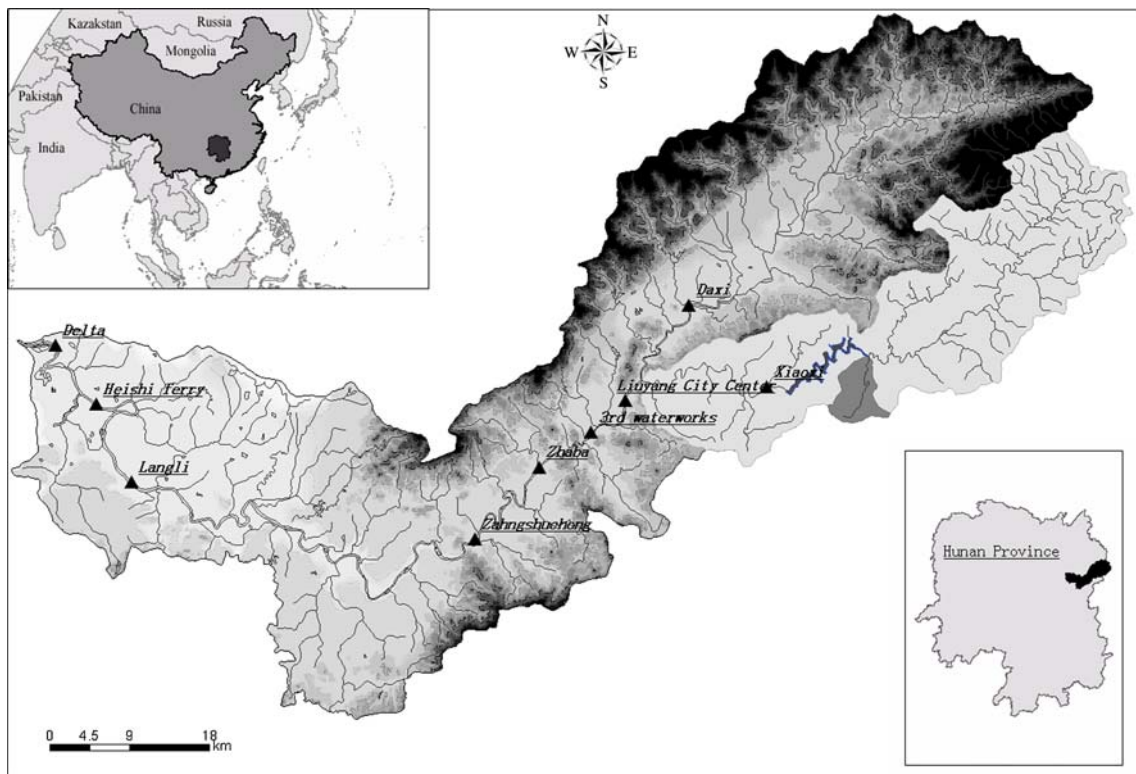


Fig. 1 Study site and location of monitoring profile

Universal pollution index calculation of each profile

Universal pollution index (PI_j) of each monitoring profile can be calculated by putting a weight. Then, every single factor pollution index can be overlay by the following formula:

$$PI_j = \sum_{i=1}^n P_i W_i \tag{2}$$

where W_i is the weight of each single factor pollution index $\sum_{i=1}^n W_i = 1$.

Determination of weight

There are many kinds of methods to determine weight, such as Expert Judgment, Delphi, but they are subjective. The research obtained the weights by excess standard rate method. The bigger the excess standard degree of monitoring value of every factor to water quality standard value, and the bigger the contribution rate to pollution, the bigger the weight. The approach was accordant with water quality standard, which was objective and feasible to practical calculation. The detailed steps of calculating weight are described below.

At first, the excess standard multiple (I_i) (The “excess standard multiple” means the degree of pollutant

concentration is higher than the National Standard for relevant water quality types) of each water quality pollutant was calculated, which was also an additional process of being dimensionless. For pollutants with high concentration, representing highly polluted, including COD, TN, TP, etc., the following formula is adopted to computing I_i

$$I_i = \frac{C_i}{S_i} \tag{3}$$

For pollutants with low concentration, such as DO, the following equation was adopted to computing I_i

$$I_i = \frac{S_i}{C_i} \tag{4}$$

where C_i is the monitoring value of i target, S_i is a mean value of each grade water quality standard for every target.

After being dimensionless for I_i , the weights of each pollutant can be calculated by the following formula

$$W_i = \frac{I_i}{\sum_{i=1}^n I_i} \tag{5}$$

Calculation of river universal pollution index

Based on universal pollution index (PI_j) of each profile, the universal pollution index of the river can be calculated by the following equation:

$$P = \frac{\sum_{j=1}^m PI_j}{m} \quad (6)$$

Where m is the number of profiles.

Assessment standards and monitoring data

In research, the adopted water quality assessment standard is the National Surface Water Environmental Quality Standard (GB3838—2002), which is a primary criterion of assessing river water environment quality. In the standard, water environment quality was divided into five types according to surface water environment function and protection objective, including river headwaters and National Nature Conservation Areas (I); first-degree conservation areas of surface water resource for centralized potable drinking water, infrequent hydrobiology habitats, spawning area of organisms like fish and shrimp, feeding areas of young fish (II); second-degree conservation areas of surface water resource for centralized potable drinking water, and water areas for fishery and swimming (III); areas for industrial water utilization, and entertainment, where people do not touch water directly (IV); water areas for agriculture, and general landscape (V). The detailed index can be seen in the Chinese National Surface Water Environmental Quality Standard (GB3838—2002). The data used in the paper includes almost 10 years' monitoring data of every monitor profile in Liuyanghe River from 1990 to 2000, which comes from Hunan Environmental Monitoring Center, and was measured by Chinese National Standard method (Zhang 2002). In some instance, data in some profiles from certain years was missing. This data was replaced by the mean value of other years for the purposes of this research.

Selection of assessment factor

Selection of assessment factors is a pivotal step, which has an important effect on assessment results. For water pollution assessment, factors affecting water environment quality could be found by stepwise selection as pivotal factors; representative factor could also be chosen by analyzing discharged pollutant properties of river pollution sources and the affecting degree of every pollutant on the river's function (Xue and Liu 2004; Ntengwe 2006). Integrating monitoring data with former research production (Luo et al. 2002), the research selected ten factors as the assessment index, including petroleum, ammonia nitrogen,

COD (Chemical Oxygen Demand), BOD₅ (Biological Oxygen Demand), DO (Dissolved Oxygen), permanganate index, TP (Total Phosphorus), TN (Total Nitrogen), Pb (Lead) and Hg (Mercury).

Result and analysis

Temporal change of water environment in Liuyanghe River watershed

Temporal change of universal pollution index

Utilizing the mentioned IUPI method, the universal pollution index of Liuyanghe River in different years could be calculated (Table 1), and the changing trend figure of universal pollution index could also be obtained (Fig. 2).

From the Table 1 and Fig. 2, it could be seen that the water quality of Liuyanghe River had a trend of gradual deterioration in the last 10 years. In 1990, the universal pollution index was 2.25, and achieved 2.71 in 1992. Although the water quality improved, and the universal pollution index decreased to 2.00 in 1993, it again increased to 3.40 in 1996 because of water pollution intensified in 3 consecutive years. In 1997, the water quality meliorated because of the closure of some industrial factories, such as chemical factories. The pollution index was only 3.00, but, the water quality was still type III, which means the water was not fit for human consumption. In 1999, the universal pollution index achieved the maximum—4.58, and the water quality belonged to type IV. In general, the change of water quality obviously took on three stages: from 1990 to 1995, the water quality type belonged to type II, and the mean universal pollution index was 2.36; from 1996 to 1998, water quality type belonged type III, and the mean universal pollution index was 3.46; in 1999 and 2000, the water quality type achieved type IV, and the mean pollution index of two year was 4.43. The increasing extent of pollution index between three stages achieved 46 and 28%, respectively. In 1993, the water quality was the best, and the pollution was only 2.00; in 1999, water quality was the worst, and pollution index achieved 4.58.

The ammonia nitrogen is a type of important pollutant influencing water quality. In the research, ammonia nitrogen was selected to study the changing trend of water quality. It can be seen that ammonia nitrogen concentration

Table 1 Universal pollution index and water quality type of Liuyanghe River in different year

Item	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Universal pollution index	2.25	2.31	2.71	2.00	2.23	2.65	3.40	3.00	3.97	4.58	4.28
Water quality type	II	II	II	II	II	II	III	III	III	IV	IV

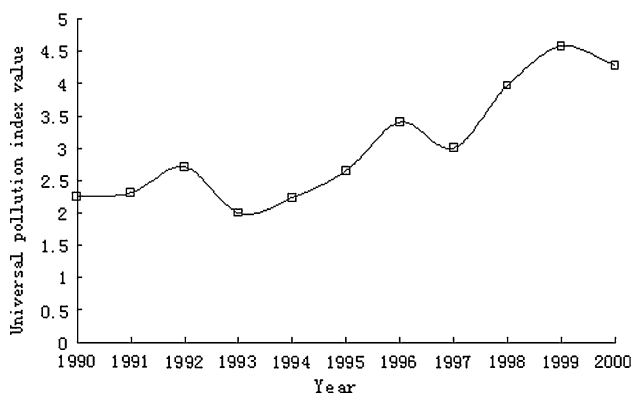


Fig. 2 Changing trend of universal pollution index

had a trend of increase by analysis of pollution factor (Fig. 3), generally, which was similar to that of Liuyanghe River’s universal pollution index.

Meanwhile, integrative regression analysis of universal pollution index was carried to study the quantitative relationship, and the regressive beeline could be obtained as follows:

$$y = 0.237x + 1.855 \quad (r = 0.883) \quad (7)$$

From the above analyses, the water quality deterioration could be observed.

Temporal change of pollution index in typical profile

For the sake of analyzing temporal changes of different area in Liuyanghe River, three typical profiles in upstream, midstream and downstream were selected to research the change of pollution index (Fig. 4), which included Xiaoxi, Zhaba and Heishi Ferry.

With the exception of the small change in water quality in the upstream Xiaoxi profile, the Zhaba profile in midstream and the Heishi Ferry profile in downstream generally presented a trend of increasingly severe pollution degree. The changes in the degree of pollution from 1993

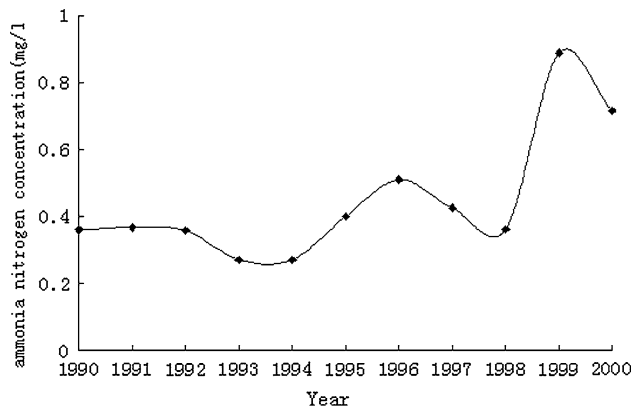


Fig. 3 Changing trend of ammonia nitrogen concentration

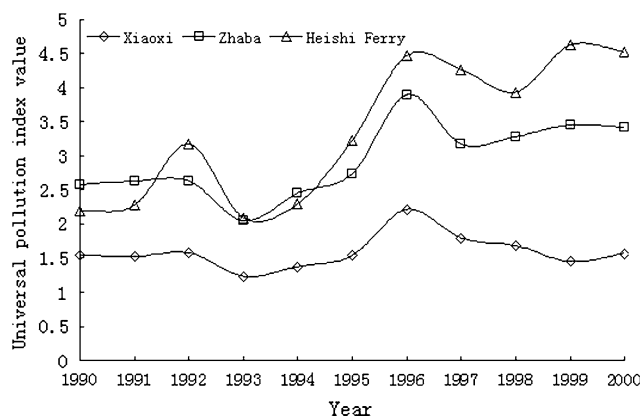


Fig. 4 Changing trends of universal pollution index in typical profile

to 1995 were very quick, and the pollution index in the Zhaba and Heishi Ferry profiles increased from 2.05 and 2.09 to 2.74 and 3.23, respectively. Their annual mean increase rates were 11.2 and 18.2%, respectively. From 1998 to 2000, the water quality of Zhaba and Heishi Ferry profiles also changed, and the mean increase rates of the pollution index in the three years were 2.1 and 5%. In 1996, the water quality was the worst, and the universal pollution indexes were 3.90 and 4.47 for the Zhaba and Heishi Ferry profiles, respectively. The trends of water quality deterioration were accordant with those of the whole Liuyanghe River watershed.

Xiaoxi River is the location of Zhushuqiao Reservoir, which would be the water supply field for drinking water in Changsha City district. As a result, the mean universal pollution index of the Xiaoxi profile, where the water quality type was type I, is the smallest, only 1.62. Even though in 1996, the water quality was the worst, the universal pollution index was still 2.22, and the water quality was type II. The result indicated that the water quality of Xiaoxi profile also has a trend of increasing gradually in recent years. Therefore, further protection of the water resources and eco-environment of Xiaoli River watershed is very important for ensuring the clean drinking water of Changsha City.

Spatial changes of surface water environment in Liuyanghe River

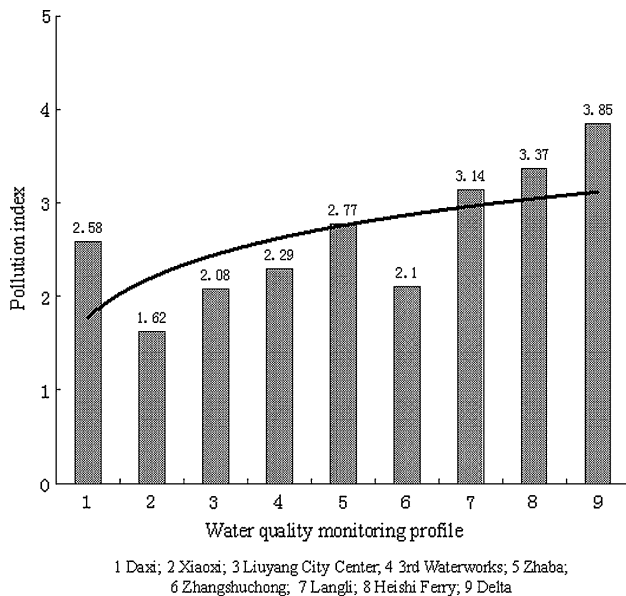
Universal pollution index changing of different profile

By the IUPI method, annual universal pollution index of each profiles were calculated, then, mean pollution index were computed (Table 2; Fig. 5).

From Table 2, Fig. 5, the trend of water quality deteriorating gradually from upstream to downstream can be seen. Because of effect of Qibaoshan Pb-Zn Mine and some chemical plants, the heavy metal content in water

Table 2 Annual pollution index and water quality type of each profiles

Item	Daxi	Xiaoxi	Liuyang City Center	3rd waterworks	Zhaba	Zhangshuchong	Langli	Heishi ferry	Deltor
Pollution index	2.58	1.62	2.07	2.29	2.77	2.10	3.14	3.37	3.85
Water quality type	II	I	II	II	II	II	III	III	III

**Fig. 5** Pollution index of each monitoring profile

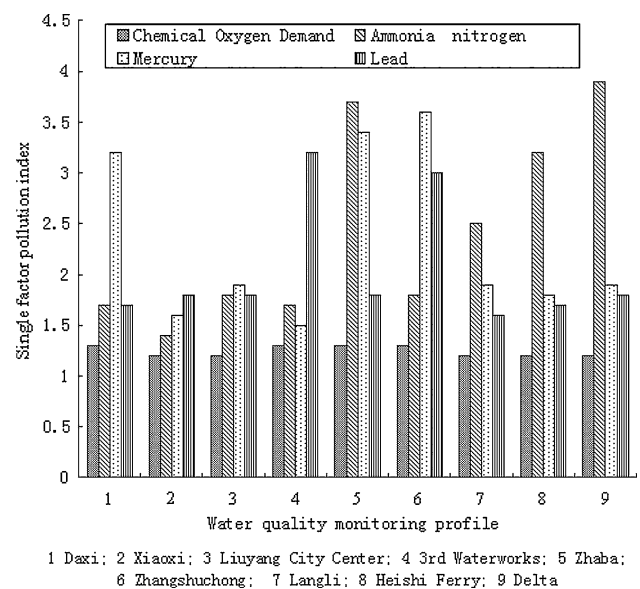
was very high, which made the universal pollution index in Daxi profile very high. As mentioned in 4.1.2, the pollution index was the smallest in Xiaoxi profile, only 1.62, and the water quality type was type I. From the Liuyang City center, 3rd waterworks to the Zhaba profile, the water quality type was type II, but the universal pollution index was ascending, and the average rate of increase was 15.8%, which showed the degree of pollution was intensifying. In the Zhangshuchong profile of Liuyanghe River's midstream, because a river branch with good water quality joined the river, the concentration of pollutant was diluted, and the degree of pollution decreased, which made the pollution index decrease to 2.07. In the downstream, the Liuyanghe River entered into Changsha County center. By reason of direct ingress of living sewage and industrial pollution sources, the water pollution intensified. The water quality of the three downstream profiles deteriorated to type III water quality, and the pollution index of the Delta profile, whose water was worst, achieved 3.85.

Single factor pollution index change of several typical pollutants for each profile

In the research, data of four factors, including COD, ammonia nitrogen, Hg, and Pb were complete. The four factors were representative for the water pollution of

Liuyanghe River, of which COD and ammonia nitrogen can reflect impact degree by organic pollution and living sewage of each profiles, and Hg and Pb could express heavy metal pollution degree. As a result, COD, ammonia nitrogen, Hg, and Pb are selected as the typical pollutant, and whose pollution indexes are calculated (Fig. 6). From Fig. 6, it can be seen that the COD pollution index of each profile varied little, between 1 ~ 1.5, which achieved the water quality standard of I type. For ammonia nitrogen, its pollution was slight in the upstream areas of Liuyanghe River, which accorded with water quality demands; in midstream, its pollution index was very high, reaching 3.7; while in three downstream profiles, its pollution index had a trend of increasing, and achieved a maximum of 3.9, which was close to water quality standards of type IV. Because of the effect of the Qibaoshan Pb-Zn mine and chemical plant, the Hg content was highest in Daxi and Zhangshuchong profile. Their Hg content exceeded the water quality standard of III type. The pollution index of Pb was much higher in the 3rd Waterworks and Zhangshuchong profiles than in others, and reached 3.2 and 3.0, respectively. The Pb content in other profiles accorded with water quality standard of I type.

As a result, it could be concluded that water quality was preferable in upstream; heavy metal pollution, including Pb and Hg, was very serious midstream; and ammonia nitrogen pollution intensified in downstream.

**Fig. 6** Single factor pollution index of each factor

Conclusions

The paper presented an IUPI method, and used it to study the temporal and spatial change of surface water environment. The research results showed the IUPI method could be utilized to assess surface water environment, effectively. Furthermore, the new approach can be much more intuitive to find the differences in the same water quality grade. Also it is a simple and easy way to assess the water quality.

1. As for temporal properties, the pollution degree of Liuyanghe River took on a trend of intensifying in the recent 10 years covered by the research based on change of universal pollution index and ammonia nitrogen concentration. The reasons, contributing to pollution, included land exploitation, plantation destruction, sewages, which led to non-point source pollution, increased ammonia nitrogen content in water, and aggravated water pollution.
2. The spatial character of Liuyanghe River's water quality had a trend of deterioration from upstream to down stream. Upstream, the water quality was good because of high forestation rates. Heavy metal—Pb and Hg pollution was serious midstream, and downstream, ammonia nitrogen pollution intensified with the development of industry and agriculture.
3. The result embodies the main benefit of the presented approach when compared with the conventional pollution index method and other complex assessing methods. The approach was simpler to users than fuzzy evaluation, matter-element model, neural network, and grey-system methods, while, factors considered are more comprehensive than conventional pollution index method. Meanwhile, the calculated universal pollution index can directly judge water quality grade (Not synthetic grading), and reflect relevant water quality grade compared with Chinese national water quality standard and the difference in the same water quality grade. Therefore, the method could be very beneficial to policy makers involved in regional water environment quality assessment, because it can allow decision makers to clearly know the current status of the water quality of their regions.

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