Front. Earth Sci. 2015, 9(3): 463–472
DOI 10.1007/s11707-015-0498-3

RESEARCH ARTICLE

Analysis of the temporal and spatial distribution of water quality in China's major river basins, and trends between 2005 and 2010

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Abstract In this study, based on environmental quality monitoring data on 22 pollutants from 490 control sections, we analyzed the spatial distribution and temporal changes of water quality in ten Chinese river basins (watersheds) to reveal the trends from 2005 to 2010. We used a comprehensive water pollution index (WPI) and the proportions of this index accounted for by the three major pollutants to analyze how economic development has influenced water quality. Higher values of the index represent more serious pollution. We found that WPI was much higher for the Hai River Basin (1.83 to 5.60 times the averages in other regions). In the Yangtze River Basin, WPI increased from upstream to downstream. The indices of some provinces toward the middle of a basin, such as Hebei Province in the Hai River Basin, Shanxi Province in the Yellow River Basin, and Anhui Province in the Huai River Basin, were higher than those of upstream and downstream provinces. In the Songhua, Liao, and Southeast river basins, WPI decreased during the study period: in 2010, it decreased by 33.9%, 44.3%, and 67.2%, respectively, compared with the 2005 value. In the Pearl River, Southwest, and Inland river basins, WPI increased by 23.1%, 47.7%, and 38.5% in 2010, compared with 2005. A comparison of WPI with the GDP of each province showed that the water pollution generated by economic development was lightest in northwestern, southwestern, and northeastern China, and highest in central and eastern China, and that the water environment in some coastal regions were improving. However, some provinces (e.g., Shanxi Province) were seriously polluted.

Keywords water environment, temporal changes, spatial distribution, comprehensive water pollution index, China, river basins

1 Introduction

River basins function as complete hydrological units that provide important support for aquatic ecosystems, but they also support regional economic development. Where the pollution generated by development is not adequately controlled, the condition of the water environment is degraded (Bhaduri et al., 2001; Ren et al., 2003; Xian et al., 2007). In recent years, the rapid development of China's economy has caused increasingly serious water pollution, but the patterns and trends vary regionally and have different characteristics (e.g., different key pollutants). According to the 2010 *Key River Basin Water Environment Quality Bulletin* released by China's Ministry of Environmental Protection (MEP), most river water quality has improved since 2005, but there are still large differences among the different river basins. Most of the existing research (Kolovos et al., 2002; Wang, 2002; Chang, 2005) has concentrated on comparisons and analysis of water quality within a single river basin (Zhang et al., 2003; Li et al., 2006; Yu et al., 2011; Wang et al., 2012a, b; Bo et al., 2013) or in several river basins (Yun et al., 2009), and the results have provided important guidance for management of the water environment of these basins. China, however, is a large country, with large differences in economic development levels among river basins, and there is also a large difference between upstream and downstream provinces. Thus, there is currently no comprehensive picture of water quality trends in watersheds throughout China. Furthermore, there has been no analysis of the relationship between economic development level and the

Received April 11, 2014; accepted November 2, 2014

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resulting water pollution in each watershed. This is a serious problem, because it prevents national managers from understanding the different needs of China's many regions and from developing and implementing a more scientific approach to managing China's aquatic environment.

Another problem is that different researchers have used different approaches, making it difficult to evaluate the spatial and temporal variations in water quality on a consistent basis. For example, researchers have used single-factor assessment (Wang et al., 2008; Liu et al., 2010; Su et al., 2011), comprehensive pollution indices (Wang et al., 2008), water quality identification indices (Liu et al., 2010), fuzzy comprehensive evaluation (Chang et al., 2001), principal-components analysis and cluster analysis (Parinet et al., 2004; Ouyang, 2005; Shrestha and Kazama, 2007; Bouza-Deaño et al., 2008; Omo-Irabor et al., 2008; Kazi et al., 2009; Wu et al., 2010), a probability transition matrix (Yun et al., 2009), a trophic level index and probability transition matrix (Chen et al., 2012), grey relational analysis and principal component analysis (Cheng et al, 2011), and improved fuzzy matter-element method (Liu, 2012). For example, Su et al. (2011) used single-factor assessment to analyze the trends in water quality in four functional zones of the Qiantang River Basin that had different river functions related to specific uses of the river. Liu et al. (2010) used a single-factor, comprehensive pollution index, fuzzy comprehensive evaluation, and water quality identification index methods to evaluate the downstream water quality in the Huai River Basin. Yun et al. (2009) established a probability transition matrix based on the theory of Markov models to forecast water quality trends for the Songhua River, Hai River, Yellow River, and Yangtze River basins. Chen et al. (2012) used a trophic level index to study the temporal and spatial variations of water quality in the Xiaojiang backwater region of the Three Gorges reservoir. Fan et al. (2010) used principal-components analysis and cluster analysis to evaluate the water quality of the Pearl River Delta. Other scholars have analyzed the status of nitrogen, organic chlorine compounds, and polycyclic aromatic hydrocarbons in the Liao River Basin, Yellow River Basin et al. (Zhang et al., 2003; Li et al., 2006; Yu et al., 2011; Wang et al., 2012a, b; Bo et al., 2013). Unfortunately, none of these researchers simultaneously studied all of China's major river basins and the changes in these basins over a long period.

Although performing a comprehensive assessment of the water quality situation using a combination of methods provides deep insights into the situation, the complexity of the calculations may decrease the applicability of the results (Liang and Jiang, 2002). In contrast, it is simpler to calculate an index value, as this is an effective way to compare status and trends of water quality on a consistent basis (Pesce and Wunderlin, 2000; Jonnalagadda and Mhere, 2001; Wayland, 2001; Popovicova, 2008). In particular, this facilitates comparisons of pollution conditions within and among watersheds (Li et al., 2010). On this basis, we chose to use a comprehensive water pollution index to evaluate the water quality in China's ten major river basins, and calculated the proportion of the pollution accounted for by the most important pollutants and pollution factors. Our goal was to provide the first comprehensive analysis of water quality throughout China at both the basin scale and the provincial or regional scale (For simplicity, we will refer to "provinces" even for parts of China such as Inner Mongolia that are formally referred to as autonomous regions.) In addition, we analyzed the relationship between pollutant levels and changes in socioeconomic development in the river basins from 2005 to 2010 to determine the relationship between water pollution and economic development. The results provide basic data and scientific guidance to support national, basin-level, and provincial plans to protect Chinese rivers and use them more sustainably.

2 Data and methodology

In this study, we obtained data for seven river basins (the Yangtze River, Yellow River, Pearl River, Songhua River, Huai River, Hai River, and Liao River basins), and three regions that combine multiple basins (the Southwest River, Southeast River, and Inland River basins). Unless otherwise noted, all data were obtained from the Chinese Ministry of Environmental Protection. We obtained data for a total of 490 monitoring sections of rivers in these basins from 2005 to 2010, and used these data to develop a time series for pollution trends in each river basin. The data included 22 water quality parameters: pH, dissolved oxygen content (DO), chemical oxygen demand based on the permanganate index (COD_{Mn}), chemical oxygen demand based on dichromate (COD_{Cr}), biological oxygen demand (BOD_5 after 5 days of incubation), ammonium nitrogen (NH_4-N), petroleum compounds (hereafter, "oils"), total nitrogen (N), total phosphorus (P), volatile phenolic compounds (hereafter, "phenolics"), mercury (Hg), lead (Pb), copper (Cu), zinc (Zn), fluoride (F), selenium (Se), arsenic (As), cadmium (Cd), chromium (Cr^{6+}), cyanide (CN), anionic surfactants, and sulfides.

To describe the water quality in each province, we calculated a comprehensive water pollution index, which is based on the proportion of the pollution accounted for by each of the abovementioned pollutants and pollution parameters. The severity of the pollution is based on a comparison of the measured value of each pollutant with the maximum acceptable value defined in the Chinese water quality standard. For each basin, we calculated the overall index based on the values from all provinces within the basin. Some provinces were included in more than one basin, and to avoid double-counting, we only accounted for monitoring data from the province's river sections that lay within a given basin. To develop priorities for pollutant control in each basin, we identified the three pollution parameters that accounted for the highest proportions of the overall pollution index. The methodology is described in the rest of this section.

2.1 Comprehensive water pollution index

We used the following equations to calculate the pollution indices (Liu, 1997):

$$\mathrm{WPI}_i = \mathrm{WPI}_{i,\mathrm{pH}} + \mathrm{WPI}_{i,\mathrm{DO}} + \sum_{j=1}^{n} \frac{c_{i,j}}{c_{j0}}, \tag{1}$$

$$\mathrm{WPI}_{i,\mathrm{pH}} = \frac{7.0-\mathrm{pH}_i}{7.0-\mathrm{pH}_{0d}}, \quad \mathrm{pH}_i \leqslant 7.0, \tag{2}$$

$$\mathrm{WPI}_{i,\mathrm{pH}} = \frac{\mathrm{pH}_i-7.0}{\mathrm{pH}_{0u}-7.0}, \quad \mathrm{pH}_i > 7.0, \tag{3}$$

$$\mathrm{WPI}_{i,\mathrm{DO}} = \frac{|\mathrm{DO}_f-\mathrm{DO}_i|}{\mathrm{DO}_f-\mathrm{DO}_0}, \quad \mathrm{DO}_i \geqslant \mathrm{DO}_0, \tag{4}$$

$$\mathrm{WPI}_{i,\mathrm{DO}} = 10-9\frac{\mathrm{DO}_i}{\mathrm{DO}_0}, \quad \mathrm{DO}_i<\mathrm{DO}_0, \tag{5}$$

$$\mathrm{DO}_f = 468/(31.6+T), \tag{6}$$

$$\mathrm{WPI} = \frac{\sum_{i=1}^{m} \mathrm{WPI}_i}{m}, \tag{7}$$

where WPI_i denotes the value of the pollution index for monitoring section i; $\mathrm{WPI}_{i,\mathrm{pH}}$ and $\mathrm{WPI}_{i,\mathrm{DO}}$ denote the measured values for water quality parameters pH and DO, respectively; pH_i, DO_i and $c_{i,j}$ denote the measured values for pH, DO and other water quality parameter j (n = 1 to 20); c_{j0} and DO_0 denote the evaluation criterion for pollutant j and DO (i.e., the maximum acceptable level) based on the evaluation criteria for Grades I to V in China's *Environmental Quality Standards of Surface Water* (GB3838-2002); pH_{0d} and pH_{0u} denote the lower and upper limits of the evaluation criterion for pH based on GB3838-2002; T denotes the water temperature; DO_f denotes saturated dissolved oxygen concentration. Each monitoring section of a river was classified as representing one of five functional zones, with different uses for each zone (e.g., to provide drinking water versus water for industrial use) and a corresponding minimum water quality (grade) required to support that use. The evaluation criterion in Eq. (1) to Eq. (5) was based on the value specified in the corresponding grade that has been defined for each function (i.e., each water use). WPI denotes the comprehensive water pollution index for the whole basin; WPI_i represents the comprehensive water pollution index for monitoring section i of the basin, obtained from Eq. (1); and m denotes the number of monitoring sections. The higher the value of WPI, the more serious the pollution. Table S1 provides details of the calculated WPI values for each province in each year of our study period.

It is important to note that WPI is a relative value; that is, it is expressed relative to each water function zone's requirements rather than representing an absolute value for the degree of pollution. Thus, one advantage of this approach is that it does not require the calculation of a "weight" for each pollutant. It also facilitates comparisons between bodies of water. For two bodies of water with the same function, an equal WPI value represents equally serious pollution; in contrast, for bodies with different functions, the same WPI value may have different meanings, but the meaning still focuses on the key function of each body of water. We can therefore evaluate the water quality in each river basin in comparison with the required quality using WPI.

2.2 Proportions of WPI accounted for by each pollution parameter

We used the following equation to calculate the proportion of the index accounted for by each pollution parameter (Liu, 1997):

$$K_j = \frac{\sum_{i=1}^{m} \mathrm{WPI}_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n} \mathrm{WPI}_{ij}} \times 100\%, \tag{8}$$

where K_j denotes the proportion of the index (WPI) accounted for by pollutant j, including water quality parameters pH and DO; n denotes the number of pollutants; and m denotes the number of monitoring sections.

3 Results

3.1 Temporal and spatial characteristics of the comprehensive water pollution index (WPI)

Figure 1 summarizes the values of WPI for the provinces in the ten river basins. The integrated pollutant indices for the provinces in the Hai River Basin were much higher than the indices in the provinces of the other basins, except Shanxi Province in the Yellow River Basin, in all years; the ratio ranged from 1.83 to 5.60 times the values in the other provinces. This is because the Hai River Basin is experiencing a severe water shortage, with little natural runoff entering the river channels. As a result, any pollution that is released into the basin's rivers cannot be sufficiently diluted. The treated wastewater from urban areas and industries also contributes to the pollution. Even when the treated water meets the Chinese standard, it adds pollution to a river that already fails to meet the standard. The quantity and quality of wastewater therefore directly influences the water quality in the Hai River Basin.

The pollutant situation shows different spatial patterns in the different basins. The integrated indices in the Hai River, Yangtze River, Songhua River, Liao River, Southeast River, and Pearl River basins increase from west to east, along the flow direction. The indices for the Southwest River and Inland River basins do not change greatly from east to west. The integrated indices are highest for Shanxi Province in the Yellow River Basin, with values ranging from 34.47 to 51.73, followed by Shandong Province in the Hai River Basin, with values ranging from 19.43 to 44.71. These values are much higher than those of other provinces in the same basin (ratios of 2.95 to 12.63 for Shanxi Province and 1.00 to 4.39 for Shandong Province). These results suggest that the production of pollutants, which is associated with socioeconomic development, is gradually shifting from eastern regions to western regions, especially for Shanxi Province in the Yellow River Basin, whose indices from 2005 to 2010 were much higher than those in other provinces (by 1.16 to 14.41 times). The pollution factors that failed to meet the Chinese standards in Shanxi Province were NH_4-N, BOD_5, COD_{Cr}, and DO. This is because Shanxi Province contains large reserves of energy, particularly coal, that are being exploited to provide energy for development, and because the promotion of a development strategy based on energy exploitation and chemical industries leads to increased pollution. The energy and chemical industries utilize more water and produce more wastes than other industries, so the demand for fresh water and the emission of wastes adversely affects the water quality in the Yellow River Basin.

From 2005 to 2010, WPI has decreased steadily in several basins: by 33.9% compared with the 2005 level in the Songhua River Basin, by 44.3% in the Liao River Basin, by 37.6% in the Hai River Basin, by 24.8% in the Huai River Basin, by 13.1% in the Yangtze River Basin, by 16.8% in the Yellow River Basin, and by 67.2% in the Southeast River Basin. In contrast, WPI has increased steadily during this period in three basins: by 23.1% compared with the 2005 value in the Pearl River Basin, by 47.7% in the Southwest River Basin, and by 38.5% in the Inland River Basin. In the Southwest River and Inland River basins, the increase in WPI indicates that the production of water pollution has spread from some downstream rivers to inland and upstream rivers as development increased in upstream regions.

3.2 Analysis of the primary pollution factors contributing to WPI

To understand the key pollutants in the basins and analyze the changes in these major pollutants during the study period, we calculated the contribution of each pollution factor to WPI from 2005 to 2010. The data of Table 1 came from the calculation of K_j in Eq. (8), which denoted the proportion of the index (WPI) accounted for by the corresponding pollutant. To define priorities for management in each basin, we have focused on the top three factors for each basin (Table 1).

Table 1 shows that from 2005 to 2010, the three main pollution factors did not change in the Yellow River, Huai

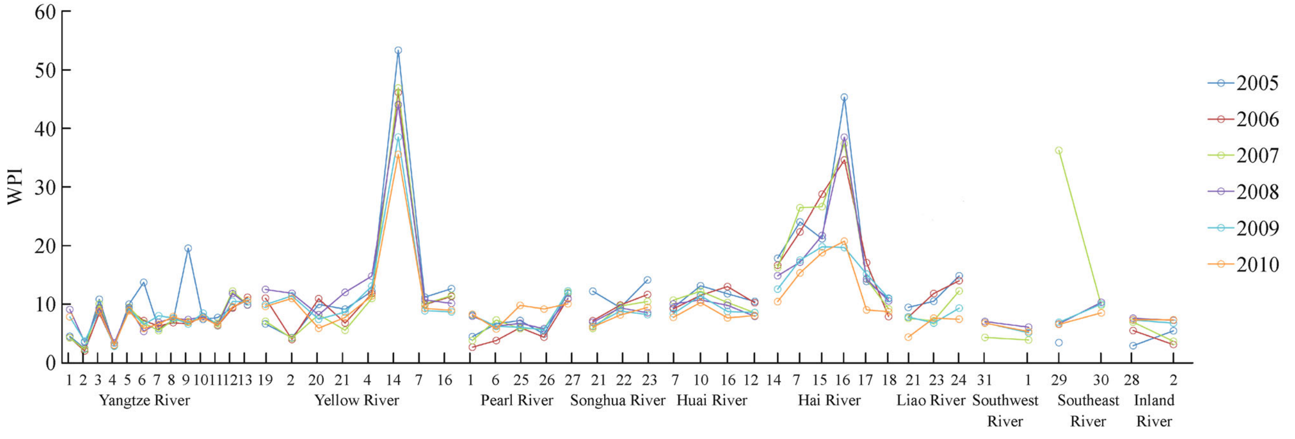

Fig. 1 Changes in the comprehensive water pollution index value (WPI) in the ten river basins from 2005 to 2010. (The data for the Southwest River Basin and Southeast River Basin were not available for 2005 and 2006.) Each number that represents a province, from left to right of the *x*-axis, is in the order of from upstream to downstream regions of a river basin. Some provinces occur in more than one basin because of the topographic characteristics of the province. Province names: 1. Yunnan, 2. Gansu, 3. Sichuan, 4. Shaanxi, 5. Chongqing, 6. Guizhou, 7. Henan, 8. Hubei, 9. Hunan, 10. Anhui, 11. Jiangxi, 12. Jiangsu, 13. Shanghai, 14. Shanxi, 15. Hebei, 16. Shandong, 17. Beijing, 18. Tianjin, 19. Qinghai, 20. Ningxia, 21. Inner Mongolia, 22. Heilongjiang, 23. Jilin, 24. Liaoning, 25. Guangxi, 26. Hainan, 27. Guangdong, 28. Xinjiang, 29. Fujian, 30. Zhejiang, 31. Tibet.

Table 1 The contributions of the three major pollutants to the comprehensive water pollution index in ten Chinese river basins at the start (2005) and end (2010) of the study period. Major pollution factors shaded in grey did not change between 2005 and 2010 for a given basin: dark grey means that none of the three factors changed, and light grey means that one or two of the three factors did not change.

Basin	Year	Contributions of the three major pollutants/%		
Yellow River Basin	2005	19.56 (Total N)	17.32 (NH_4-N)	8.04 (BOD_5)
	2010	35.05 (Total N)	15.01 (NH_4-N)	7.04 (BOD_5)
Hai River Basin	2005	18.46 (NH_4-N)	13.33 (Total N)	11.38 (BOD_5)
	2010	35.10 (Total N)	16.46 (NH_4-N)	8.74 (Total P)
Pearl River Basin	2005	18.16 (Total N)	7.93 (DO)	7.59 (Se)
	2010	26.61 (Total N)	10.25 (NH_4-N)	9.39 (DO)
Liao River Basin	2005	14.58 (NH_4-N)	13.71 (Phenolics)	12.69 (BOD_5)
	2010	19.37 (NH_4-N)	9.58 (COD_{Cr})	9.52 (BOD_5)
Southeast River Basin	2005	17.28 (COD_{Mn})	14.96 (Oils)	14.83 (DO)
	2010	25.95 (Total N)	10.05 (Oils)	8.58 (COD_{Cr})
Yangtze River Basin	2005	21.27 (Hg)	15.73 (Total N)	8.75 (Total P)
	2010	25.97 (Total N)	9.55 (Total P)	7.33 (COD_{Cr})
Huai River Basin	2005	19.44 (Total N)	15.36 (NH_4-N)	9.24 (COD_{Cr})
	2010	24.66 (Total N)	9.92 (NH_4-N)	9.89 (COD_{Cr})
Songhua River Basin	2005	12.70 (Total N)	11.74 (COD_{Mn})	10.97 (COD_{Cr})
	2010	18.06 (Total N)	12.50 (COD_{Mn})	11.55 (COD_{Cr})
Southwest River Basin	2005	13.91 (Pb)	12.24 (pH)	11.17 (COD_{Cr})
	2010	10.82 (Pb)	9.03 (DO)	8.41 (COD_{Cr})
Inland River Basin	2005	15.76 (pH)	13.35 (BOD_5)	12.85 (NH_4-N)
	2010	21.04 (Total N)	15.67 (Oils)	7.83 (COD_{Cr})

River, and Songhua River basins. The main pollutant factors in the Yellow River Basin were total N, NH_4-N, and BOD_5; in the Huai River Basin they were total N, NH_4-N, and COD_{Cr}; and in the Songhua River Basin, they were total N, COD_{Mn}, and COD_{Cr}. Therefore, organic pollution was the main problem in these three basins. Only one factor changed in the Yangtze River, Hai River, Pearl River, Liao River, and Southwest River basins. In the Yangtze River Basin, Hg changed to COD_{Cr}; in the Hai River Basin, BOD_5 changed to total P; in the Pearl River Basin, Se changed to NH_4-N; in the Liao River Basin, volatile phenolics changed to COD_{Cr}; and in the Southwest River Basin, pH changed to DO. Thus, organic pollutants again ranked in the top three factors. The Inland River Basin differed from the other basins because all three dominant factors changed between 2005 and 2010, although organic factors remained dominant. Therefore, the water pollution in all of the river basins in China was dominated by organic pollutants throughout the study period.

3.3 Analysis of the relationship between economic development and water pollution

Based on the results of our analysis of WPI, we used data on the gross domestic product (GDP) in 2010 to categorize the ten Chinese river basins. Table S2 provides GDP values for each of the provinces in each year of our study period. First, we arranged WPI and GDP in ascending order, and calculated their median values. On this basis, we calculated a median of 8.1 for WPI and of $1{,}020\times10^9$ CNY for GDP, and used these medians as a dividing line that defined four different types of relationship between pollution and development (Fig. 2).

On this basis, the lower left corner of the graph shows low pollution and low economic intensity (the "low intensity zone"), the top left corner of the graph shows high pollution and low economic intensity (the "excessive pollution zone"), the top right corner of the graph shows high pollution and high economic intensity (the "unsustainable proportional zone"), and the bottom right corner of the graph shows low pollution and high economic intensity (the "relatively sustainable zone"). Figure 3 shows that the number of provinces in the low intensity zone decreased in 2010, with provinces from the Yangtze River, Yellow River, Pearl River, and Inland River basins belonging to this zone in both years. More provinces were in the excessive pollution zone in 2005 than in 2010, but Shanxi Province had by far the highest WPI value in both years, which means that managers must focus on reducing water pollution in this province. In the unsustainable proportional zone, the level of economic development is

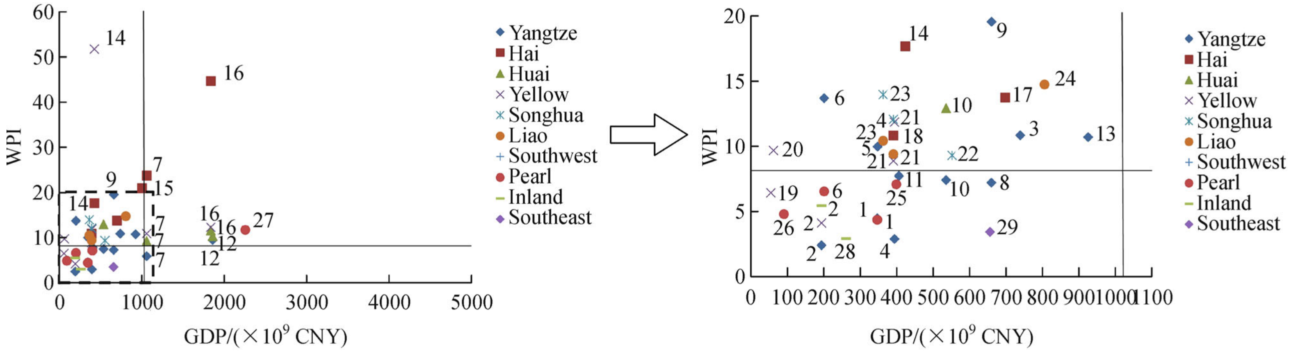

Fig. 2 The classification of the ten Chinese river basins in 2005 based on the median parameter values. Solid lines: WPI, comprehensive water pollution index (a median of 8.1); GDP, gross domestic product (a median of 1,020×10^9 CNY). The dashed lines represent the position of the enlarged area shown at the right side of the figure. Province names: 1. Yunnan, 2. Gansu, 3. Sichuan, 4. Shaanxi, 5. Chongqing, 6. Guizhou, 7. Henan, 8. Hubei, 9. Hunan, 10. Anhui, 11. Jiangxi, 12. Jiangsu, 13. Shanghai, 14. Shanxi, 15. Hebei, 16. Shandong, 17. Beijing, 18. Tianjin, 19. Qinghai, 20. Ningxia, 21. Inner Mongolia, 22. Heilongjiang, 23. Jilin, 24. Liaoning, 25. Guangxi, 26. Hainan, 27. Guangdong, 28. Xinjiang, 29. Fujian, 30. Zhejiang, 31. Tibet.

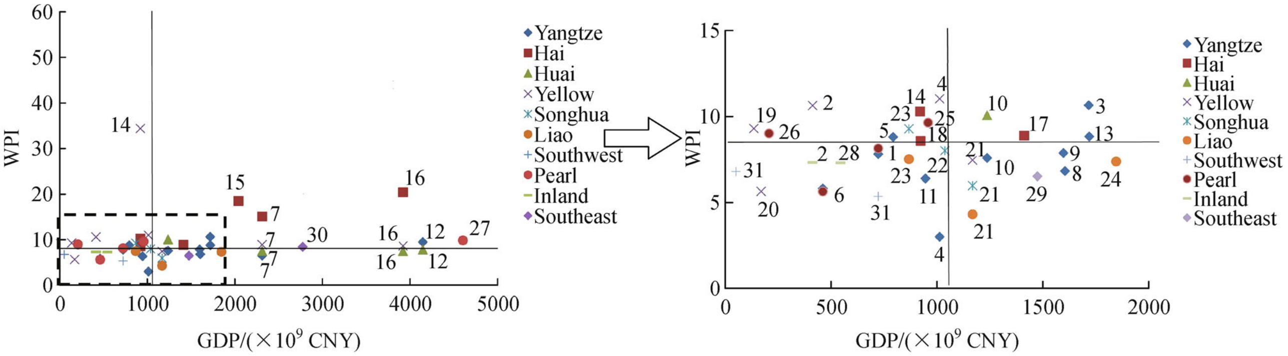

Fig. 3 The classification of the ten Chinese river basins in 2010 based on the median parameter values. Solid lines: WPI, comprehensive water pollution index; (a median of 8.1); GDP, gross domestic product (a median of 1,020×10^9 CNY). The dashed lines represent the position of the enlarged area shown at the right side of the figure. Province names: 1. Yunnan, 2. Gansu, 3. Sichuan, 4. Shaanxi, 5. Chongqing, 6. Guizhou, 7. Henan, 8. Hubei, 9. Hunan, 10. Anhui, 11. Jiangxi, 12. Jiangsu, 13. Shanghai, 14. Shanxi, 15. Hebei, 16. Shandong, 17. Beijing, 18. Tianjin, 19. Qinghai, 20. Ningxia, 21. Inner Mongolia, 22. Heilongjiang, 23. Jilin, 24. Liaoning, 25. Guangxi, 26. Hainan, 27. Guangdong, 28. Xinjiang, 29. Fujian, 30. Zhejiang, 31. Tibet.

proportional to WPI, and the number of provinces belonging to this zone increased between 2005 and 2010. This trend cannot be ignored because the rapid development is accompanied by equally rapid increases in pollution of the water resources. In the relatively sustainable zone, the number of provinces increased between 2005 and 2010. Because this represents rapid development without correspondingly high levels of pollution, managers can learn lessons from this zone that can be applied to reduce pollution in other zones.

4 Discussion

To reveal the spatial and temporal variations in water quality within Chinese river basins, researchers have used a range of methods. For example, Liu et al. (2010) used the single-factor, comprehensive pollution index, fuzzy comprehensive evaluation, and water quality identification index methods to evaluate water quality in the lower reaches of the Hai River in 2009. They found that water pollution was serious in this area and that the main pollutants were total N, NH_4-N, COD_{Cr}, BOD_5, COD_{Mn}, and F; thus, the dominant pollution was organic. In our study, many of the same pollution factors were among the most important factors (total N, NH_4-N, BOD_5), although there were some differences (e.g., COD_{Mn} was more important in Liu's study and total P was more important in the present study), and the pollution of rivers in the southern Hai River Basin was more serious than that in the north. In our study, WPI was highest for Shandong Province in the south of the Hai River Basin, which agrees with the results of Liu's study. Yun et al. (2009) established a probability transition matrix based on Markov theory and used it to predict water quality trends for the Songhua River, Hai River, Yellow River, and Yangtze River basins based on data from 27 monitoring points along the four rivers. They concluded that the water quality in the four rivers showed only limited improvement in 2005. From January to December, water quality in the Hai River Basin became worse, whereas that in the Songhua River Basins became stable, which partly agrees with our results for the change from 2005 to 2006. Chen et al. (2012) used a trophic level index to study the temporal and spatial variation in water quality in the Xiaojiang backwater region of the Three Gorges reservoir. They found very high total N and total P in this region from 2008 to 2010. The water was slightly eutrophic, but the water became less eutrophic after 2008. Our results for the Yangtze River Basin show that from 2005 to 2010, the water quality improved slightly, but that total N and total P remained major pollutants, and organic pollution remained the dominant form.

Su et al. (2011) studied 13 monitoring factors in 41 monitoring sections of the Qiantang River Basin based on monitoring data from 1998 to 2004, and used the single-factor assessment method to analyze the water quality trends during this period. They found that the main pollution factors were COD_{Mn}, NH_4-N, Cd, and F, and that despite slight fluctuations, these factors remained mostly stable. In the present study, the Southeast River Basin included 18 rivers, including the Qiantang River. Because our study covered a much larger number of rivers, the only factor that was similar between the two studies was COD_{Mn}, and that was no longer one of the three dominant factors in the Southeast River Basin by 2010. Fan et al. (2010) used principal-components analysis and cluster analysis to evaluate the water quality in the Pearl River Delta, and found that the North River, East River, and West River had severe, moderate, and light pollution, respectively. In our study, we found that in 2005, WPI was 9.21 for the North River, 7.62 for East River, and 15.35 for West River, which was not completely consistent with the study of Fan et al. (2010). This difference is likely to be due to the fact that Fan et al. only considered seven pollution factors (DO, COD_{Mn}, BOD_5, total P, NH_4-N, oils, and Hg), whereas we considered 22 factors. In addition, the concentration of Se in our study was 6.27 mg/L in the West River in 2005, which was 62.7 times the standard value of 0.01 mg/L. The number of evaluation factors considered in a study clearly influences the evaluation results.

In general, pollution is relatively light in the northwestern, southwestern, and northeastern regions but severe in the central and eastern regions. However, pollution levels in economically developed coastal areas are improving. Water quality was much worse in Shanxi Province of the Yellow River Basin than in any other province, and was worse in Shandong Province in the Hai River Basin than in other provinces of that basin. These regional differences have largely resulted from China's economic development strategy, which initially prioritized eastern coastal cities. These cities have implemented the reforms under China's official "opening up" policy since around 1978. After more than 30 years of rapid development, their economic development level is therefore far higher than those of inland regions. In the eastern and coastal regions, water quality deteriorated badly as a result of rapid economic development unconstrained by measures to protect the environment, but in recent years, environmental management has been implemented and the industrial structure has been gradually adjusted. For example, small and inefficient enterprises such as those in the paper-making, chemical, printing, and dyeing industries have been shut down. Sewage treatment facilities have been established for both cities and industrial parks. As a result, water pollution is becoming less severe. In addition, many enterprises responsible for heavy pollution loads have gradually been moved to the central and western regions. Currently, the economy of the central regions is still undergoing industrialization, accompanied by growing water pollution, so the situation there is not optimistic, unless measures are taken to protect the watersheds.

Our results suggest that water pollution has gradually shifted from the eastern regions to the western and central regions, and the water quality of China's western and inland rivers has continuously worsened. The outlook for water pollution in western regions is therefore pessimistic. Limitations on the natural and social conditions in the central and western regions mean that the water resource is limited and its self-purification ability is poor. Under its current western development strategy, the Chinese government plans to intensify development in western and northwestern China. It is clear that the policy of transferring industries to the west will also transfer the burden of pollution to this region. It will be a significant challenge to improve western development while still protecting the environment, thereby avoiding the high cost of remediation after pollution has occurred. The problems that have occurred and that are being solved in the eastern regions since 1978 can provide lessons for newly prioritized development areas such as central and western China.

By calculating the contribution of each pollution factor to WPI from 2005 to 2010, we analyzed the differences of major pollution factors and their changes over time among the various river basins. For a long time, due to the combustion of coal and accumulation of manure, soil in the Yangtze River Basin had a high background value for Hg. Coupled with the sewage discharged by the chemical industry, by light industry, and by medical device manufacturers along the river, Hg became a major water pollution factor. But with the promotion of the "5531 Project", which aimed to curb the deterioration of water quality in the Yangtze River Basin, the urban industrial layout and the industrial structure of this region have been adjusted, and pollution control efforts have intensified, thereby gradually reducing emissions of pollutants such as Hg in wastewater. However, since 2003 when water storage began at the Three Gorges Dam, the flow velocity slowed in the Yangtze River, reducing the river runoff and diminishing the water's self-purification ability. As a result, the environmental capacity to dilute or detoxify pollutants decreased, and simultaneously, COD_{Cr} and NH_4-N increased. Thus, the problem of eutrophication became increasingly prominent, and organic pollution was still an important factor.

The Hai River Basin had more highly developed industrial and agricultural operations than other regions, so phosphorus discharge intensified in urban and industrial wastewater in the upper reaches, whereas the amounts of pesticides and fertilizer from farmland increased in downstream regions of the river, with large quantities of residual nitrogen flushed into the Hai River by rainfall. Therefore, nutrients became a major source of pollution in the Hai River Basin.

Some counties in the Pearl River Basin had a long history of mining, and poorly regulated exploitation of the region's mineral resources led to a significant problem with Se pollution. Heavy metal pollution in the Pearl River Basin directly threatened the quality and safety of the region's water. However, in recent years, special campaigns have been conducted to monitor mining companies, particularly illegal operations, and these measures have begun to effectively curb the heavy metal pollution. As a result, in 2010, contamination by Se and other heavy metals was no longer a major factor.

In the Liao River Basin, wastewater discharge from the region's many oil-refining, coking, paper, and ammonia plants created high concentrations of volatile phenolics in the basin, and these compounds became one of the main pollution factors. But in 2010, COD_{Cr} replaced volatile phenolics as one of the three major pollutants. This change was caused by rapid development in cities in Liaoning Province of the Liao River Basin, accompanied by discharges of wastewater that contained large amounts of oxygen-consuming organic matter. In addition, nonpoint-source agricultural pollution, including rural sewage, fertilizers, pesticides, and livestock wastewater, caused a significant increase in the concentration of organic pollutants.

Identifying relationships between the major pollution factors and their main sources would help managers propose effective measures to control water pollution within a basin. The importance of studies such as ours is that they can provide a scientific basis for integrated river basin management. We used Duncan's multiple-range test in version 20.0 of the SPSS software (http://www-01.ibm.com/software/analytics/spss/) to test for significant differences in WPI from 2005 to 2010. For each river basin, we calculated WPI for each province based on the values of each of the 22 water quality parameters in that province. Table S3 provides significance of the differences in WPI for each province in the ten river basins studied from 2005 to 2010.

Our test showed significant differences in water quality among the provinces within the following river basins: in the Yellow River Basin (from 2005 to 2010), the Pearl River Basin (from 2005 to 2007), and the Hai River Basin (2005 and 2008). No other basin showed significant differences among its provinces in any year. The significant differences in the Yellow River Basin mainly resulted from significantly higher values of DO, COD_{Mn}, BOD_5, NH_4-N, Pb, COD_{Cr}, total N, total P, anionic surfactants, and sulfides in Shanxi Province than in the other provinces. In the Pearl River Basin, the significant differences from 2005 to 2007 resulted mainly from the severe water pollution in Guangdong Province. However, water quality in Guangdong Province subsequently improved and pollution in Yunnan Province and Hainan Province increased, leading to no overall difference in water quality among the provinces of the Pearl River Basin. The Hai River Basin was the most polluted, and water pollution in Shandong Province was the most serious in this basin, whereas the water quality in Tianjin Municipality was better than that in other provinces. However, in 2009 and 2010, management of the water environment in the Hai River Basin became more effective, and water quality in each province improved to some extent, especially in Shandong Province. Thus, the difference in water quality among the provinces in this basin also decreased and became non-significant. Overall, the proportion of the river basins that showed significant differences in water quality among their provinces was low (19.6%); that is, the differences in water quality among a basin's provinces were generally not significant. In future research, we hope to perform a deeper analysis of the meaning of the differences in WPI in each river basin.

5 Conclusions

In this study, we used an integrated pollution index to evaluate water quality in China's ten major river basins, identify trends, and provide scientific support for the development of policies to mitigate China's severe water pollution problems. To our knowledge, this is the first study to provide an overview of the pollution problem throughout China's river basins using a consistent index that allows comparisons between basins and between regions within a basin, thereby revealing priorities for the development of remediation strategies. As for the spatial distribution of water quality, we found that the Hai River Basin was significantly more polluted than the other river basins, and should therefore become a priority for improved management. The water quality in the Yangtze River, Hai River, Songhua River, Liao River, Pearl River, and Southeast River basins decreased gradually from upstream to downstream, which suggests a need to improve pollution management in upstream regions so that less pollution reaches downstream regions. The water quality changed little from the upper to the lower reaches in the Southwest River and Inland River basins, suggesting that relatively little transport of pollution occurs within these basins; nonetheless pollution levels are sufficiently high throughout these basins that measures must be implemented to prevent further increases. As for the temporal changes of water quality, water pollution seems to be gradually shifting from the eastern coastal regions to the central and western regions of China, and has gradually expanded into upstream regions and inland rivers.

Our analysis of the major pollution factors suggests targets for priority management. Organic pollution was a major problem that must be addressed in the Yellow River, Huai River, and Songhua River basins. Dominant factor changes in other river basins suggest a need for ongoing monitoring to allow managers to focus their efforts on new pollutants as their efforts begin to control previously identified pollution priorities. Under the combined effects of rapid urbanization, changes in the urban layout, industrial restructuring, and pollution control measures cause the main pollution factors for each river basin to change both spatially and temporally, reinforcing the need for ongoing monitoring.

Analysis of the relationship between economic development and water quality revealed that water pollution was more severe in the central and eastern regions, and that pollution was improving in the highly economically developed coastal areas. The water in some individual provinces (particularly Shanxi and Shandong Province) is seriously polluted, and governments must prioritize these problem provinces. However, in some regions, rapid development has not been accompanied by severe pollution, and governments should look for lessons they can learn from the successes of these regions.

The present analysis is based on a large amount of data. However, in our analysis of the relationship between water pollution and GDP, we relied on the value of the integrated pollution index at a provincial level, which provides insufficient resolution to support localized measures to control pollution. We also relied on annual-resolution data rather than more precise data on the changes during the year, since data with finer resolution were not available for all control sections in our study. In the future, it will be necessary to obtain data with higher spatial and temporal resolution and to deepen our analysis by combining the present approach with methods such as factor analysis and cluster analysis.

Acknowledgements This work was supported by the Fund for Innovative Research Group of the National Natural Science Foundation of China (Grant No. 51421065), by the Program for New Century Excellent Talents in University (No. NCET-12-0059), by the National Natural Science Foundation of China (Grant No. 41171068), and by Beijing Natural Science Foundation (No. 9154037).

Supplementary material is available in the online version of this article at http://dx.doi.org/10.1007/s11707-015-0498-3 and is accessible for authorized users.

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