Spatiotemporal variation of surface water quality for decades: a case study of Huai River System, China

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ABSTRACT

Characterization of spatiotemporal variation of water quality is a basic environmental issue with implications for public health in China. Trends in the temporal and spatial distribution of water quality in the Huai River System (HRS) were analyzed using yearly surface water quality data collected from 1982 to 2009. Results showed that the water quality of the main stream deteriorated in the 1990s and early 2000s but has been ameliorated since 2005. The sections that were classified as severely polluted from the monitoring data were located largely in the middle reach. The water quality of HRS fluctuated during the period 1997–2009; it has improved and stabilized since 2005. In terms of spatialized frequency of serious pollution, heavily polluted regions were mostly concentrated in the area along several tributaries of the Ying, Guo and New Sui Rivers as well as the area north of Nansi Lake. These regions decreased from 1997 to 2009, especially after 2005. Our analysis indicated that water pollution in HRS had a close relation with population and primary industry during the period 1997–2009, and implied that spatiotemporal variation of surface water quality could provide a scientific foundation for human health risk assessment of the Huai River Basin.

Key words | Huai River System, spatiotemporal variation, surface water quality, water pollution

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INTRODUCTION

Rivers supplied the ever-growing water resource demands of social and economic development and received more and more pollutants from industrialization, agriculture, and increasing population. As a result, an ecological and health crisis developed that would be exacerbated if the quantity and quality of water resources were not appropriately managed (Peters *et al.* 1997). China has not been an exception to this emerging crisis and many reports have pointed out that some regions in China have suffered from this crisis in the past decades (Chen *et al.* 2005; Appleton *et al.* 2006; Beaumont *et al.* 2008). Among the seven river basins in China, the Huai River Basin (HRB) has been well-known for serious water pollution since the 1990s (Zhou & Wang 2005). In 2004, the domestic media widely reported that some villages in HRB had high mortality from digestive cancer (Wan *et al.* 2011) and the relationship between cancer and water pollution has attracted considerable attention from the public and administration. Accordingly, scientists were sponsored to determine the influence of water quality change on public health by both the local and national governments, so that they could suggest effective measures (Tao 2010). In previous studies, water quality management (Xia *et al.* 2011), pollution factors (Zhang & Huang 2011) and the relation between dams and water quality were the main research focus on water quality of Huai River System (HRS) (Zhang *et al.* 2010). However, very little work has been done on the spatiotemporal variation in the water quality of HRS over a timescale of several decades.

Previous studies have used statistical methods, including principal component analysis, cluster analysis and discriminant analysis to determine dynamic changes in water quality indicators in temporal trends, and to represent spatial features of water quality via grouping monitoring stations into clusters (Alberto *et al.* 2001; Bengraine & Marhaba 2003; Singh *et al.* 2004). For small-scale areas, water is homogenous; methods like spatial interpolation and contour could be applied directly to display the spatial variation in water quality (Wu *et al.* 2011). For large-scale areas, such as a basin, rivers are regarded relatively discrete in

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two-dimensional surface and parameters of surface water are only meaningful for the area actually covered with surface water. Therefore, geo-statistics or spatial methods are not suitable to analyze monitoring data directly. In some research, the study area was segmented by buffer zones of rivers (Choe *et al.* 2008) or hydrologic response units (Ferrier *et al.* 2001; Lam *et al.* 2012) to obtain the spatial distribution of water quality for a whole basin. Hence, it is feasible to spatialize water quality data for rivers when the buffer zone or sub-basin are taken as the spatial unit, then concurrent analysis of water environment factors and socioeconomic factors could also be achieved.

Here, we investigated the spatial and temporal trends in surface water quality of the HRS using spatial methods based on surveillance data obtained from 1982 to 2009. This study will contribute to water pollution control in HRS and provide a scientific foundation for evaluation of the influence of water pollution on human health in HRB.

MATERIAL AND METHODS

Study area

The HRB is located in eastern China (Figure 1(a)) between the Yellow River to the north and Yangtze River to the south (longitude E111°55′–122°45′, latitude N30° 55′–38°20′). The basin covers five provinces and 203 counties, with an area of 270,000 square kilometers. It is the most densely inhabited river basin and the main agricultural area of China. The west, southwest and northeastern parts of the basin are mountainous and hilly, which accounts for about one-third of the total area; the remaining part is a vast plain. The HRS is a typical parallel river system with many long tributaries on the north shore of the main stream, flowing through the Huang-Huai Plain, and a few short tributaries on the south shore, passing through mountains and hills. The main lakes in the watershed are Nansi Lake in the north, and the Hongze and Gaoyou Lakes in the south.

Data collection

In this study, surface water quality data of HRS came from 1983 to 2010 National Environmental Quality Reports released by the Ministry of Environmental Protection of China (Environmental Protection Administration in 1983–2008), including location of monitoring sections, water quality grades and indicators. Water quality was classified into six grades based on the annual average concentration of each indicator in these reports according to the Environmental Quality Standards for Surface Water (2002) (Table 1). There was no record of Grade I in HRS from 1982 to 2009 in these reports. The other grades were divided into three groups in this paper: Grades II and III were waters of good quality, Grade IV represented lightly polluted water; and Grade V and worse than Grade V were heavily polluted water (represented by Grade V–V+).

The monitoring sections were not evenly distributed spatially: sections on the main stream were mostly located on the middle reach in Anhui Province; sections of tributaries were mainly distributed on reaches crossing the provincial boundary of Henan and Anhui Provinces and reaches in Shandong and Jiangsu Provinces (Figure 1(a)). There were a few sections before 1997, but by 2002 there were 86 stable sections (Figure 2(a)). Therefore, analysis of water quality in the HRS was mainly based on data from 1997 to 2009. There were five to 18 sections along the main stream before 2003, stabilizing at 14 after that. The proportion of sections at each different water quality grade was determined to calculate the level of contamination each year; in addition the proportion of years that each section remained at a certain water quality grade was calculated.

Additionally, statistical yearbooks of the five provinces in HRB from 1997 to 2009 were gathered and sorted as socioeconomic indices at the county-scale. Digital Elevation Model (DEM) with a 90 m resolution was collected from United States Geological Survey (USGS) for undertaking hydrology analysis. In this paper, spatial and mathematical statistical analyses were carried out in SPSS 18.0 (SPSS Inc.) and ArcGIS 10.0 (ESRI Inc.), respectively.

Frequency of serious pollution

The ratio of occurrences of Grade V–V+ to total observations, named as Frequency of Serious Pollution (FSP), reflects the overall pollution status of the sections with long-term monitoring data available.

We took the sub-basin as the spatial analysis unit. The spatialization of FSP was performed using the following steps: (1) FSP was calculated and treated as an attribute value for each section point; (2) 18 sub-basins were extracted through DEM using hydrology module in ArcGIS; (3) Inverse Distance Weighted (IDW) interpolation of ArcGIS was utilized to spatialize FSP in each sub-basin; and (4) results of step 3 were spliced using the mosaic tool in ArcGIS.

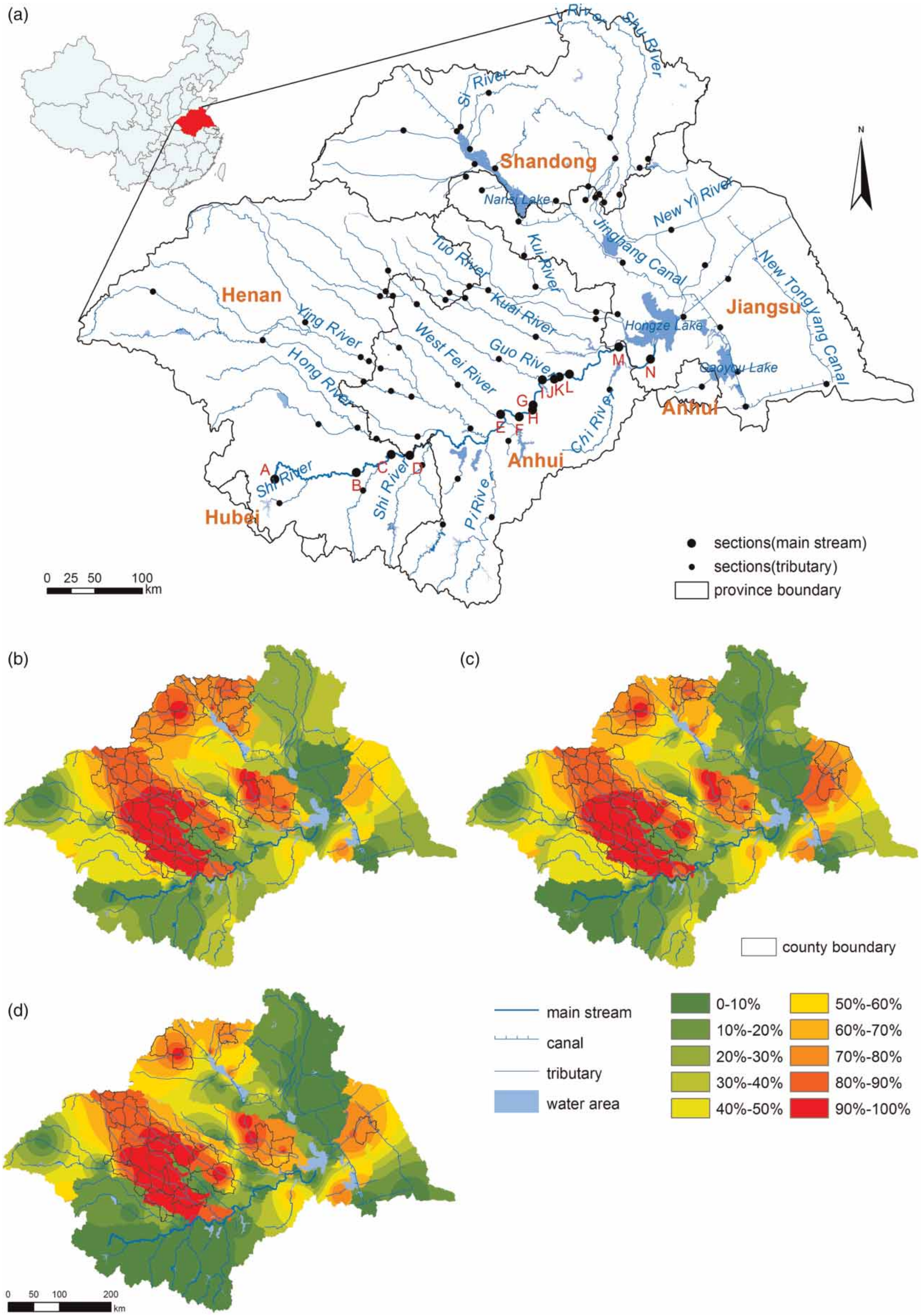

Figure 1 | (a) Water system and monitoring sections. Spatialized FSP of water quality and counties with FSP greater than 70% in the period 1997–2009 (b), 2001–2009 (c) and 2005–2009 (d).

Table 1 | Water quality grades and concentration range of some indicators in the Environmental Quality Standards for Surface Water (2002)

	Concentration range (mg/L)				
Grades	Ammonia nitrogen	Total nitrogen	Total phosphorus	BOD_5 (5-day biochemical oxygen demand)	COD (chemical oxygen demand)
I	≤ 0.15	≤ 0.2	≤ 0.02	≤ 3	≤ 2
II	≤ 0.5	≤ 0.5	≤ 0.1	≤ 3	≤ 4
III	≤ 1.0	≤ 1.0	≤ 0.2	≤ 4	≤ 6
IV	≤ 1.5	≤ 1.5	≤ 0.3	≤ 6	≤ 10
V	≤ 2	≤ 2.0	≤ 0.4	≤ 10	≤ 15
V+	> 2	> 2.0	> 0.4	> 10	> 15

RESULTS AND DISCUSSION

Statistical analysis

According to the fluctuation of the proportion of sections at Grade V–V+ as illustrated in Figure 2(b), water quality in the mainstream of HRS suffered from serious pollution from 1986 to 2005, especially in the period 1991–1996. Since 2005 it has started to ameliorate noticeably: the proportion of Grade II–III increased, while the proportion of Grades IV and V–V+ decreased. There were differences in the water quality between monitoring sections on the mainstream (Figure 2(c)): good for the upper reach (Sections A–C) (Figure 1(a)), poor for middle reach (Sections D–L) and lower reach (Sections M–N). For Sections B, D, E, G, K and L, the percentage of years at Grade V–V+ was close to or exceeded 30%, and reached 60% for Section G.

According to the proportion of the three groups of water quality grades, the temporal trends related to the water quality in HRS divided into three periods (Figure 2(d)): (1) 1997–1999, water quality gradually ameliorated in terms of decreasing proportion of Grades IV and V–V+ and increasing proportion of Grade II–III; (2) 2001–2004, the percentage of Grade V–V+ increased dramatically in 2001 and was still larger than 50% until 2004, percentage of Grade II–III was about 20% in this period; and (3) 2005–2009, proportion of Grade II–III continued increasing from 2005 and firstly exceeded Grade IV and then Grade V–V+ from 2008 onwards (Figure 2(d)).

Spatiotemporal trends of FSP

According to the spatial distribution of FSP in the period 1997–2009 (Figure 1(b)), the level of pollution on the north shore of the Huai River was much higher than that on the south shore, while the middle reaches had higher pollution levels than the upper and lower reaches. Seriously polluted regions were concentrated in areas along the tributaries of the Ying and Guo Rivers (Region I), Kui and New Sui Rivers (Region II) and the northern area of Nansi Lake (Region III). These regions were mostly on the boundaries of two provinces, such as the Henan–Anhui provincial boundary (Region I), Anhui–Jiangsu boundary (Region II) and Shandong–Jiangsu boundary (Region III).

The average FSP of each county was computed with the zonal statistics tools in ArcGIS. As a result, 47 counties, which accounted for 23% of the total, had an average FSP of more than 70% in the period 1997–2009 (Figure 1(b)). The number of such counties was 40 and 30 in the period 2001–2009 and 2005–2009 (Figures 1(c) and 1(d)), with percentages of 20 and 15% for all the counties, respectively. There was also a noticeable decline in the FSP after 2005 in regions that did not have a high FSP value to begin with, especially the southern and northeastern parts of the basin.

Spatial analysis of county-scale FSP

For each county in HRB, population density and ratio of production value of primary industry to the total production value of each year were calculated. The average value of these two indices from 1997 to 2009 were significantly correlated with the average FSP from the same period at the county-scale (Table 2), and the correlations were both positive. These two indices were mapped in Figure 3, which was also overlaid by the 47 counties with a FSP greater than 70% during the period 1997–2009. The middle area of the basin had a larger population density as well as a greater primary industrial production ratio when compared to the eastern

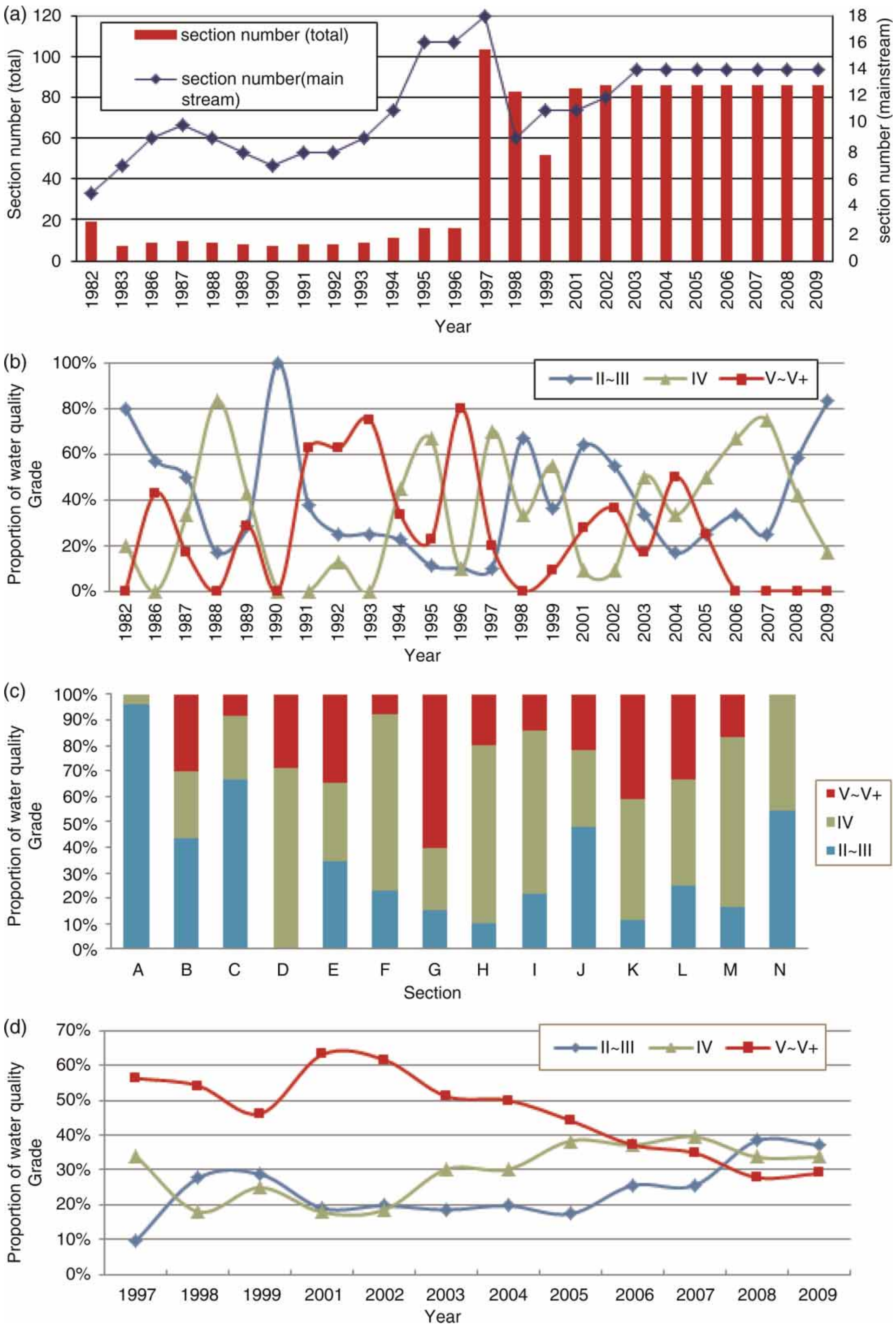

Figure 2 | (a) The number of monitoring sections during the period 1982–2009 in HRS, (b) proportion of sections of different water quality grades for each year of the mainstream, (c) proportion of years of different water quality grades for each section of the mainstream, and (d) proportion of sections of different water quality grades for each year of HRS.

and western areas. Most counties with a FSP value greater than 70% were in the middle area of the north shore of the mainstream, with denser population and less developed economies.

Water pollution control in HRB

Point sources (industrial and domestic sewage) and agricultural non-point sources were the main pollutant

Table 2 | Correlation analysis between socioeconomic indices and FSP of HRB during the period 1997–2009

	Average population density	Average ratio of output value of primary industry to the total production value
Correlation coefficient	0.320[a]	0.311[a]
Number of counties	181	173

[a]Correlation is significant at the 0.01 level (two-tailed).

sources for HRS, although the former was dominant (Xia *et al.* 2011). Early in 1994, many comprehensive measures were taken by four provinces (Henan, Anhui, Jiangsu and Shandong) to control water pollution (Zhou & Wang 2005), but the pollution was still serious, especially in the period 2001–2004 (Figure 2(d)). Until 2004, when water quality at the trans provincial boundary reaches was considered to be an important regulation in evaluating governments' performances, enhanced control and management of enterprises in HRB gradually decreased the discharge of industrial wastewater and resulted in an apparent amelioration of surface water quality (Tan *et al.* 2005). In this study, it can be seen that the water quality has improved and stabilized since 2005 (Figure 2(d)) and the area of high FSP noticeably decreased in the period 2005–2009 (Figure 1(d)).

However, during the period 2005–2009 FSP remained very high at the center of the region with great concentration of heavy pollution, despite the water quality generally improving. In other words, the current amelioration of water quality is only the result of preliminary control of the severe pollution. Our study also indicated that FSP had a significant correlation with population and production value of primary industry (Table 2). Domestic sewage, fertilizer and pesticide usage increased continuously and became dominant pollutant sources in association with population growth and agricultural development in the watershed (Song *et al.* 2011), but were not targeted by sufficient management actions. Therefore, there is still much to be done to control surface water pollution in HRB in the future.

Water pollution and human health

A centralized water supply covered only 28.9% of the rural population in HRB, below the national average of 55.1%. Only a limited amount of drinking water came from deep wells with the majority coming from rivers, canals, ponds or shallow ground water (Tao 2010). According to the investigation by the Chinese Center for Disease Control and Prevention (China CDC) in 2005, the area along the tributaries of the Ying and Kui Rivers had historically low mortality from digestive cancers in the 1970s but high risk of this kind of cancers in recent years (China CDC 2010). In our study, these regions had suffered from serious surface water pollution for more than 10 years (Figures 1(b)–1(d)). The main reason for rural drinking water quality not reaching prescribed health standards in China was due to surface water pollution (Luo & Ye 2005). In the polluted water environment, there were not only contaminants such as nitrite and nitrate, but also toxic algae caused by eutrophication (Yu *et al.* 2001), both of which are harmful to the human digestive system and potentially a cause of high risk for digestive cancers (Ueno *et al.* 1996; Mayne *et al.* 2001; Xie *et al.* 2011). We speculate that most people living in the rural areas in HRB were probably exposed to these harmful substances in drinking water for several years. However, this revelation should be further investigated by considering more water quality indicators, in addition to topography, soil, living habits, medical conditions and other factors in further research.

Limitations

A few limitations of this study warrant mentioning. Firstly, the surveillance data available prevented a more detailed investigation from being undertaken. Spatiotemporal variation in water quality of HRS was only analyzed from 1997 to 2009, due to missing monitoring data from some stations before 1997. Secondly, water quality, in terms of classifications from Grades I to V+, was not as good as the observed concentration of the water quality indicators that reflected the degree of water pollution comprehensively. Although deficient, these surveillance data published by a branch of government were reliable. Thirdly, it was assumed that FSP was relatively independent between sub-basins. This meant that data from sections located in the sub-basin were mainly used to carry out the interpolation of FSP. Due to the limited amount and uneven distribution of monitoring sections in HRS, the spatialization of FSP had to find a balance between the number of sub-basins and number of sections in each sub-basin. Detailed geographical differences inside the sub-basins were ignored when FSP was spatialized by IDW, such as topography, length and discharge of rivers. Despite this,

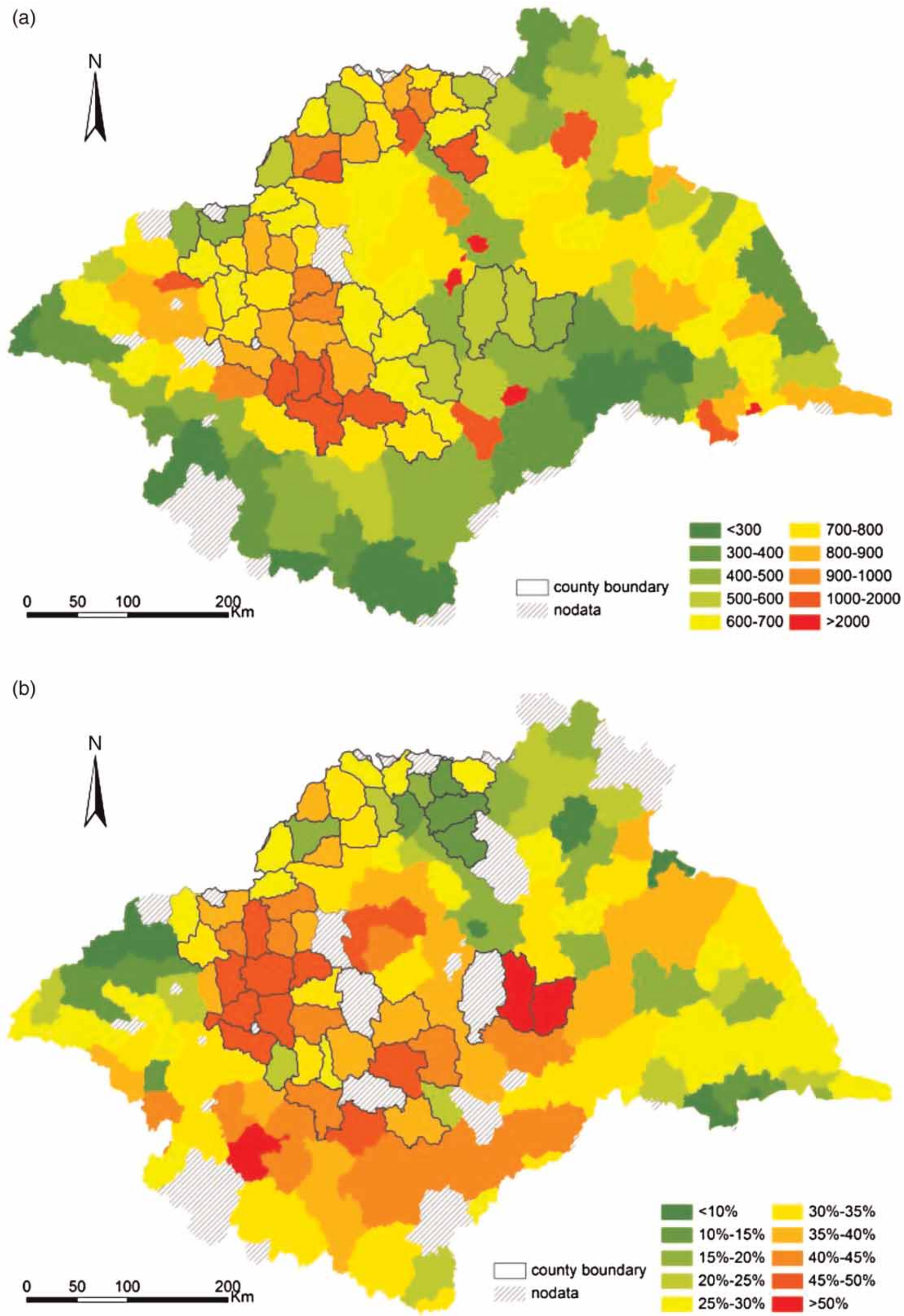

Figure 3 | (a) Average population density and (b) average ratio of output value of primary industry to the total production value with counties with FSP greater than 70% during the period 1997–2009 in HRB.

it was effective to express the difference between sub-basins at large scale. In addition, further studies could be carried out between FSP and other factors such as climate and land use.

CONCLUSIONS

In conclusion, surface water quality of HRS has been ameliorated since 2005, but that of some tributaries is still poor. We suggest that more effective measures should be further undertaken to improve water quality in these tributaries, such as non-point pollution control and domestic sewage treatment. Moreover, detailed water quality indicators should be collected in future research for the investigation of the intrinsic relationship between water quality and human health risk in this basin.

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