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Spatial correlations between urbanization and river water pollution in the heavily polluted area of Taihu Lake Basin, China

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Abstract: Water pollution in the Taihu Lake Basin has been the focus of attention in China and abroad for a long time, due to its position in the forefront of urban development in China. Based on data gathering and processing from 84 monitoring sections in this heavily polluted area, this study first analyzes spatial patterns of urbanization and the distribution of river water pollution, and then uses the GeoDa bivariate spatial autocorrelation model to investigate the spatial correlation between urbanization and river water pollution at the scale of township units. The results show that urbanization has adverse impacts on water pollution, and the influence varies in different levels of development areas. The urban township units have the highest level of urbanization and highest pollution, but the best water quality; the suburban units have lower level of urbanization, but higher pollution and worse water quality; however the rural units have the lowest level of urbanization and lowest pollution, mainly affected by upstream pollution, but worst water quality. Lastly, urban and rural planning committees, while actively promoting the process of development in the region, should gradually resolve the issue of pollution control lagging behind urban life and urban development, giving priority to construction of centralized sewage treatment facilities and associated pipeline network coverage in the rural areas and suburban areas.

Keywords: urbanization; river water pollution; spatial correlation; heavily polluted area

1 Introduction

Urbanization became an irreversible global change during the 20th century (UNFPA, 2007).

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Although the experience has proven the importance of urbanization to poverty eradication, economic development, and modernization, urbanization—especially rapid urban development in currently developing countries—has had negative impacts on environmental quality at local, regional, and global scales (IHDP, 2005). Drastic conflicts between scarcity and pollution have made water resources a key restricting factor for sustainable urbanization processes (Bao and Fang, 2007). Water security has become a political issue in some regions (OECD, 2005) as a result of land cover change and intensified human activity from urbanization (Butler and Schütze, 2005; Olivera and DeFee, 2007). As "a living laboratory in urbanization" (Normile, 2008), China has experienced fast economic development and rapid urbanization in the past three decades. Because of the lack of sanitation and the uneven distribution of water treatment facilities, as is found in most developing countries (Cohen, 2006; Society for International Development [SID], 2008), rapid urbanization in China has resulted in surface water eutrophication and reduced water quality (Yu *et al*., 2011; Deng and H, 1999; Lei *et al*., 2012).

The Taihu Lake Basin is the most developed area in China (Hu *et al*., 2008). Recently, the area has been in the forefront of the urbanization process in China (Su *et al*., 2010), while at the same time it is a pivotal, ecologically sensitive zone. Even after years of comprehensive treatment of the water environment, the water quality of the Taihu Lake Basin is unstable and knocking its ecosystem out of balance (Stone, 2011). River inflows are the main source of pollutants to the lake watershed, inducing serious ecological and sanitary problems (Gibert and Wendy, 2003; Kunwar *et al*., 2005). Surface water pollution in the Taihu Lake Basin has become increasingly serious, restricting the sustainable development of the local economies (Jin, 2000; Li *et al*., 2000; Li, 2005; Zhao *et al*., 2013; Sun *et al*., 2011; Sun *et al*., 2010). With the rapid formation of economic zones, led by Shanghai, the pace of urbanization in the Taihu Lake Basin will also accelerate and the area is predicted to comprise the biggest megalopolis in China by the year 2020 (Su *et al*., 2010). As a result of this increased development, loads on the ecology and environment will be aggravated, and potential water environmental crises will have increased effects (Li, 2005). Thus, improvement of the urban water environment is an important issue for the future.

In recent years, the relationship between urbanization and water quality of the surrounding surface water bodies has been extensively studied (Bhaduri *et al*., 2000; Duh *et al*., 2008; He *et al*., 2008; Fu *et al*., 2009). In particular, a number of urban-rural transect studies have identified the impacts of urbanization on surface water quality (Callender and Rice, 2000; Brett *et al*., 2005; Schoonover *et al*., 2005; Tsegaye *et al*., 2006; Alberti *et al*., 2007; Foster and Cui, 2008; Wang *et al*., 2008; Li *et al*., 2009; Bao C, Fang C L, 2009). Research has documented that high population growth and lack of sewage systems lead to surface water pollution (Al-Kharabsheh, 1999; Al-Kharabsheh and Ta'any, 2003); subsequently, Yu *et al*. (2011) and Yin *et al*. (2005) confirmed that urban population growth rate was strongly related to surface water quality, as a result of the contribution of untreated domestic wastewater and non-point pollution sources to waterways. Wang *et al*. (2008) affirmed that spatial and temporal variations of surface water quality were significantly affected by the level of urbanization, as measured by an integrated pollution index in Shanghai, China, between 1982 and 2005. Chang (2008) examined 118 sites in the Han River Basin of South Korea and concluded that urban land cover was positively associated with increases in water pollution and was an important variable in water quality parameters. In general, these studies used statistical analyses to identify possible links between various aggregate land uses and water quality indicators measured over a relatively long period at a large scale. Only a few studies have been conducted at a relatively smaller scale to consider particular characteristics of development, such as population density (Atasoy *et al.*, 2006; Fu *et al.*, 2009).

In the urban planning process, however, it is important to understand not only the relationships between urbanization and water pollution in general, but also more specifically how development patterns (for example, population density and occupancy) may influence various water pollution indicators so that potential environmental impacts can be mitigated. This paper takes an innovative and completely different approach, using the GeoDa bivariate spatial autocorrelation model to examine the impact of urbanization on river water pollution from the perspective of township units. Case studies on water pollution related to urbanization in the heavily polluted area of the Taihu Lake Basin, China, will be useful as a reference for other developing regions with similar environmental problems caused by rapid urbanization.

This paper is structured as follows: An overview of the study area is found in Section 2. Description of the data acquisition and research methods are presented in Section 3. Section 4 contains the results and discussion, depicting the distribution of urbanization and water environmental pollution, and calculating spatial correlations between them. Concluding remarks and further discussions are given in Section 5.

2 Study area

The study area is located in the western Taihu Lake Basin. It is named the heavily polluted area, due to its pollutant discharges being heavily influenced the water environment, through most of rivers flowing into the Taihu Lake. It covers parts of two prefecture-level cities, Changzhou and Wuxi, among which the parts of Changzhou City include five districts, i.e., Xinbei, Zhonglou, Tianning, Qishuyan and Wujin, and the parts of Wuxi City cover 6 districts and one county-level city, i.e., Huishan, Beitang, Chong'an, Nanchang, New District, Binhu and Yixing City (Figure 1). The total area is approximately 5271.6 km^2, accounting for 14.3% of the whole Taihu Lake Basin (36,895 km^2). In recent years, especially after 2000, the heavily polluted area began a rapid development phase with an annual GDP increase of 20.0%, that is, its gross domestic product (GDP) grew from 1.63×10^{10} dollars (USD) in 2000 to 6.91×10^{10} dollars (USD) in 2008. Moreover, there were 7.44×10^6 inhabitants (20.6% of the local total) in 2007 and the population density was 1412 person/km^2, up to 1.16 times that of the Taihu Lake Basin as a whole and more than 10 times that of the average for China (134 person/km^2). In 2007, the total wastewater discharge in the whole area was 4.47×10^9 t accounting for 0.8% of China. In the same time, the wastewater discharge per capita was 60.1 t, but that of China only 42.1 t/person, moreover, the wastewater discharge per square kilometer was 8.5×10^5 t and was 14.6 times that of China (5.8×10^4 t). Additionally, this area is densely covered by a water network, including Taihu Lake and 18 rivers, and numerous other water bodies. Among the rivers, Wuyi Canal, Caoqiao River, Taige Canal, Xilicao River, Wujin Port, Cailing Port, Zhihu Port, Zhandu Port, and Hengtang River contribute most of the water and pollution inputs to Taihu Lake, the third largest freshwater lake in China (Li *et al.*, 2000). During the rapid economic growth and urbanization, surface water pollution has become a serious issue.

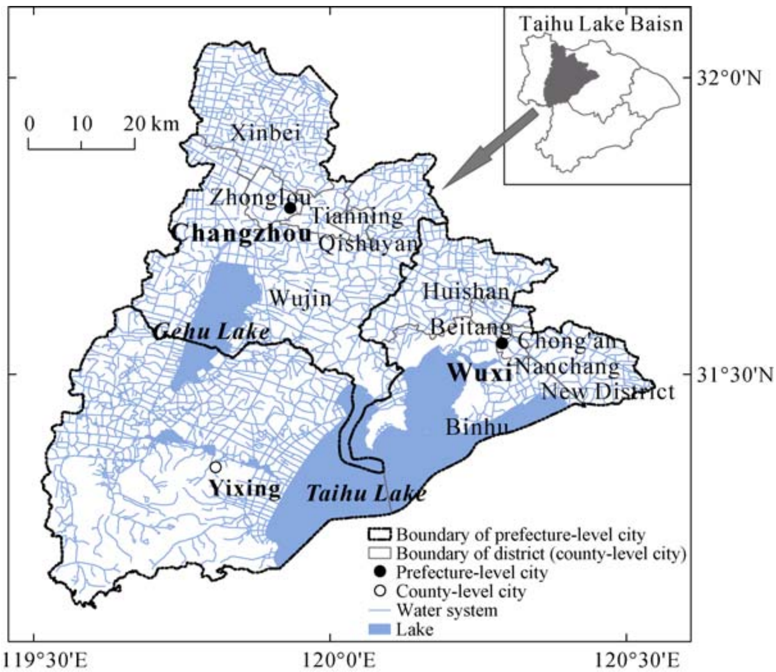

Figure 1 Location of the study area

3 Data acquisition and methods

3.1 Urbanization indicators and classification

Anthropogenic activities have had significant effects on water quality in the local rivers (Wang *et al*., 2007). However, it is impossible to determine the variety and amount of pollutants in urban surface runoff, their loads in receiving waters, and subsequently to indicate surface water quality, from variables of land use/cover change alone. Economic constitution (or industrial structure) and population density are more appropriate for indicating urbanization impact on surface water quality because pollutants result from economic development and human consumption (Yu *et al*., 2011). Population size is an important parameter affecting the total volume of discharged domestic wastewater in the sewer system (Fu *et al*., 2009). Therefore, the ratio of urban population indicates the urbanization level in this study. Based on the ArcGIS spatial analysis module, the rate of urbanization is classified into five ranks.

The population data came mainly from the statistical yearbooks and population census; a few townships' population data were amended through field research and interviews in 2007. In addition, economic and social data involved in this study came from the Wuxi statistical yearbook (WMSB, 2001, 2008) and the Changzhou statistical yearbook (CMSB, 2001, 2008).

3.2 Water quality monitoring and classification

3.2.1 Sampling sites and monitoring

To comprehensively reflect river water pollution and test the influence of urbanization, 84 monitoring sections on main rivers that connect to the lake were selected from Wuxi City

Environmental Quality Report in 2007[1] and Changzhou City Environmental Quality Report in 2007[2]. Among them, Changzhou 40, Wuxi City 31, Yixing 13, including Jinniu Bridge, Pingling Bridge, Nanyun Bridge, Cailing Bridge, Weidun Bridge, Zhongtian Steel, Daixi Bridge, Yao Lane, among others (specific locations are shown in Figure 2).

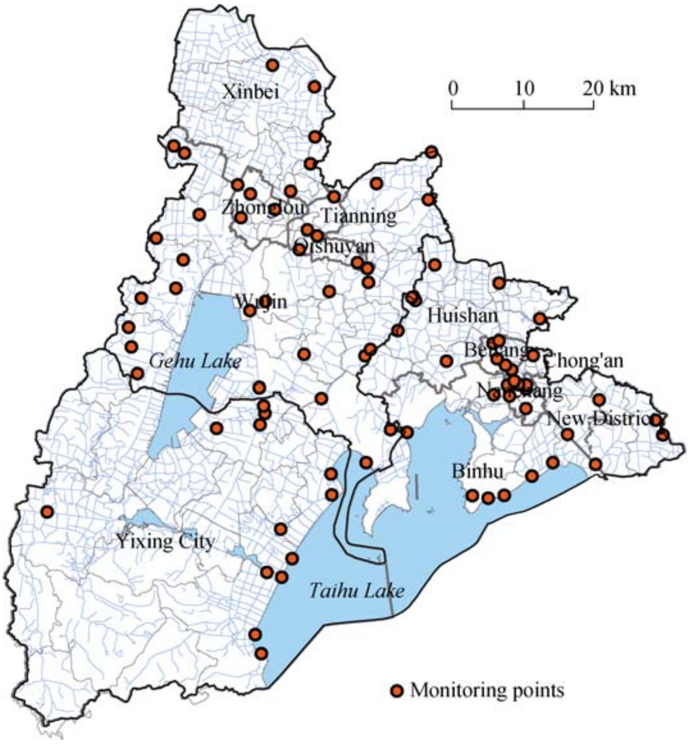

Figure 2 Distribution of monitoring points

The monitoring specifications for river water quality use the "water environment monitoring standards" (SL219-98; MWRC, 1998). Monitoring frequency was six times a year, every sampling site was observed in a single month. The measuring indexes were chemical oxygen demand (COD), ammonia nitrogen (NH_3-N), total nitrogen (TN), and total phosphorus (TP).

3.2.2 Water quality classification

With single factor index method water quality at the sampling sites is classified into five categories, according to the Chinese Government Standard for Water Quality issued in 2002 (GB 3838-2002) (Table 1). Subsequently, water quality in the study area was evaluated systematically and superposition of different indicators was analyzed with the ArcGIS spatial analysis module. The single factor index method equation is shown as follows:

$$G = \mathrm{MAX}(G(i)) \tag{1}$$

where $G(i)$ is the water quality category of i pollutant.

[1] Wuxi City Environmental Protection Bureau, 2010. Wuxi City Environmental Quality Report (2007).

[2] Changzhou City Environmental Protection Bureau, 2010. Changzhou City Environmental Quality Report (2007).

Table 1 The surface water environmental quality standards for basic items (mg/L)

Indexes	Category I	Category II	Category III	Category IV	Category V
COD	15	15	20	30	40
NH_3-N	0.015	0.5	1.0	1.5	2.0
TP	0.02	0.1	0.2	0.3	0.4
TN	0.2	0.5	1.0	1.5	2.0

Note: Taken from the literature (State Environmental Protection Administration of China, 2002).

3.2.3 Water environmental pollution discharge

Data on water environmental pollution discharge in 2007 were calculated according to the general population, per capita domestic water consumption and sewage discharge coefficient. As the main and conventional index measuring water environmental quality, indicators of COD, NH_3-N, TN, and TP are used to analyze the distribution of water environmental pollution discharge.

3.3 Spatial correlation analysis between urbanization and water pollution

Spatial analyses were conducted by using GeoDa software. In searching for the relationship between urbanization and water pollution, the urban population proportion is compared against water pollution parameters in a space autocorrelation model; based on the coupling results, the study area was clustered under township units and divided into groups.

As a result of the impact of spatial interactions and spread, the geographic data may be no longer independent from one to another but related; in this case local indicators of spatial association (abbreviated LISA) are suitable to fully reflect spatial differences in economic trends. In other words, LISA can be used to measure the concentration and dispersion effect of a small area centered on each geographical unit and to identify spatial clustering (hot or cold spots) and outliers (Anselin, 1995). Thus, this paper uses LISA to study the match between urbanization and water pollution among different township units, using the following equation:

$$I_i = \frac{\left(x_i - \bar{x}\right)}{S^2} \sum_{j=1}^{n} w_{ij} \left(x_j - \bar{x}\right) \tag{2}$$

$$S^2 = \frac{1}{n} \sum_{i=1}^{n} \left(x_i - \bar{x}\right)^2 ; \quad \bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \tag{3}$$

where n is the number of units involved in the analysis of space, x_i, x_j is the observation in region i and region j respectively, $\bar{x}$ is the average of the observation, and w_{ij} is the adjacency matrix between i and j. Given the p of significance level, if I_i is much greater than 0, the spatial difference is weak between region i and its surrounding areas, on the contrary, if I_i is much less than 0, the spatial difference is evident.

Additionally, in order to eliminate the dimensional differences between the various indicators, a maximum difference standardization method is used, which is calculated as follows:

$$X_{ij} = \frac{x_{ij} - x_{i\min}}{x_{i\max} - x_{i\min}} \tag{4}$$

where X_{ij} is the standardized value of i in township j, $x_{i\max}$ is the maximum value among i, $x_{i\min}$ is the minimum value, and x_{ij} is the initial value of i in township j.

4 Results and discussions

4.1 Levels of urbanization and classification

Driven by rapid development, the study area has urbanized continuously; as a result, the urban rate (ratio of urban population to the total) reached 64% in 2007, the highest in the entire Taihu Lake Basin. At the same time, the annual growth rate of urbanization was 1.3%–1.5% in the past two decades, which was higher by 0.3%–0.5% than that of Jiangsu province as a whole. However, there are large differences among rates of urban development in this area, as seen from their distribution (Figure 3). That is, the highest rate areas where urbanization rates above 67.3% are mainly located in the eastern part of the study area. Moreover, areas with rates between 39.7% and 67.3% are situated in suburban areas, which surround the downtown areas. Urbanization rates less than 39.7% are scattered in rural areas, mainly in the western part of the study area. The rates show an overall distribution pattern of concentric circles, with the highest rates in urban areas, the next highest rates in suburban areas, and then scattering to the lowest rates in rural areas.

The process of urbanization in the study area is driven by the Sunan model[3] and by booming township enterprises; consequently, the older urban areas began to take shape around industries. With the usage of resources and discharge of pollutants limited by environmental capacity, especially polluted industries have migrated outside the urban areas; as a result, the suburban and rural areas are developing urban centers.

4.2 Spatial patterns of pollution discharges

The procession driven by industrialization has many characters; rapid development is accompanied by a large number of pollutants with increased discharge concentrations and by heavy impact on the water environment. In 2007, there were 306 million metric tons (t) of municipal domestic wastewater, 112.3 thousand t of chemical oxygen demand (COD), 15.7 thousand t of ammonia nitrogen (NH_3-N), 20.6 thousand t of total nitrogen (TN), and 1.7 thousand t of total phosphorus (TP) discharged in the heavily polluted area of the Taihu Lake Basin. The township or street level distribution of pollution discharges (see Figure 4) shows that the heaviest pollution was concentrated in urban areas, lessening in suburban areas, with the lightest pollution scattered in rural areas. In other words, wastewater pollutants are mainly discharged from downtown and suburban areas, of which municipal wastewater discharges account for 77.9% of the total. With the distribution of COD as an example, Xinbei District, Tianning District, Gaoxin District, Binhu District, and Nanchang District have the highest discharges exceeding 7 thousand t. Parts of Zhonglou District, Qishuyan District,

[3] Sunan model is the integration of urban-rural relations law in the process of industrialization and urbanization since Chinese reform and opening up, which originated in the southern region of Jiangsu Province, including Suzhou City, Wuxi City, and Changzhou City.

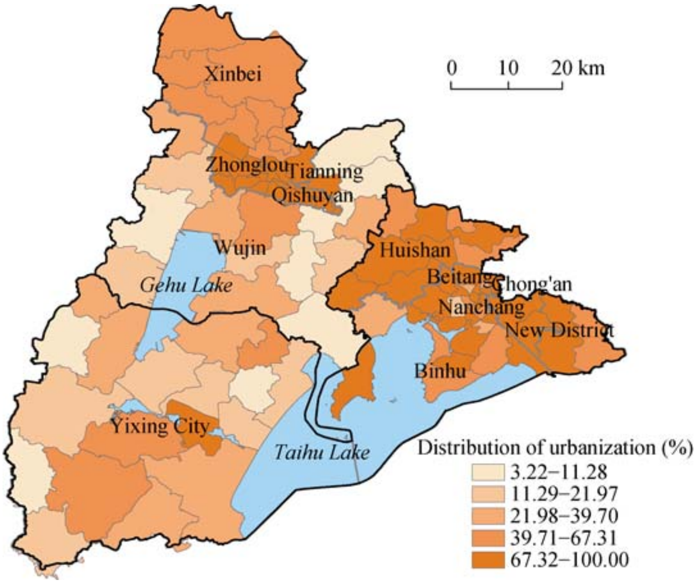

Figure 3 Distribution of urbanization

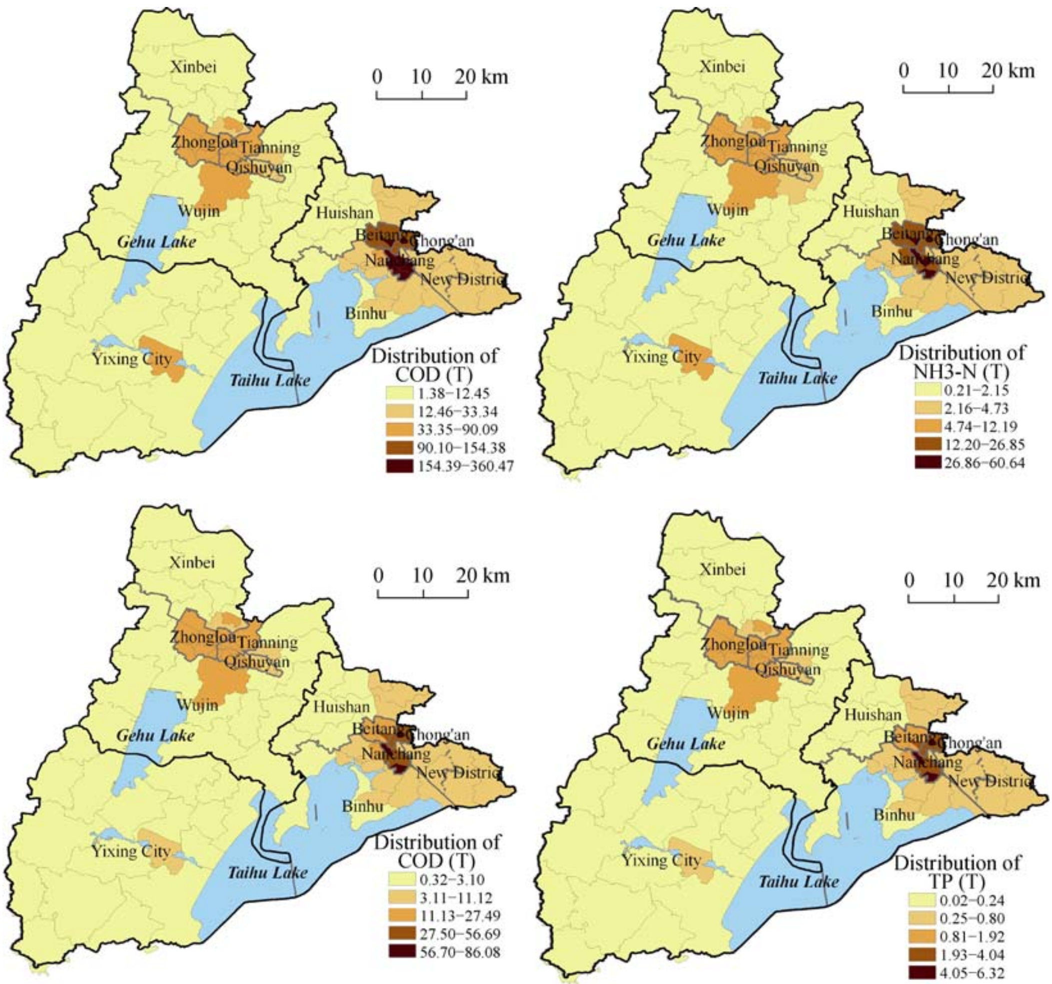

Figure 4 Distribution of pollution discharges

Beitang District, and Chong'an District had discharges in the second rank, with discharges of more than 1.5 thousand t. The other areas had the lowest discharges of less than 1.5 thousand t.

As we have seen, the distribution of pollution discharges follows the pattern of urbanization. The combined effects from population density, fast and intense urbanization, delayed construction of centralized sewage treatment facilities, and other factors, especially population increasing more than the expected scale of urban development planning, meant that water pollution control capacities were weak. Although some towns have sewage treatment plants, treatment capacity was designed only based on the domestic sewage discharge of local residents, which makes current treatment needs difficult to meet because of faster urbanization and larger municipal wastewater discharge. So, a larger proportion of the contribution to the regional water quality and eutrophication in Taihu Lake has come from the pollution load in the water (Stone, 2011).

4.3 Spatial correlation between urbanization and river water pollution

The COD indicator failed a significance test, so TN, TP, and NH_3-N were selected for the GeoDa bivariate spatial autocorrelation model. On the basis of the results of coupling between urbanization rate and water pollution indicators, the study area was clustered under township units and divided into four groups, that is, high urbanization rate–high pollution discharge (H-H), low urbanization rate–high pollution discharge (L-H), low urbanization rate–low pollution discharge (L-L), and non-correlation.

4.3.1 The spatial autocorrelation between urban development and TP

From the distribution of the relation between urbanization and TP (Figure 5), it can be seen that the H-H group is mainly found in the downtown areas of Changzhou City and Wuxi City in the eastern part of the study area. The haphazard urban development and increased population in these areas outstripped the sewage treatment plant's expected scale, aggravated municipal wastewater discharge and created a shortage of treatment facilities.

The L-H group is mainly found in suburban areas of Wuxi City, which are along Xicheng Canal and Lihe River, and in areas surrounding the main inlet of the Taihu Lake. A negative correlation between the proportion of non-agricultural population and TP pollution discharge exists in these regions.

The L-L group is mostly found in the western part of the study area, in rural areas of Changzhou City and Wuxi City, which are around the east and west sides of Gehu Lake and along tributaries of the Lihe River on both sides.

The spatial autocorrelation between non-agricultural population and TP was not significant in other regions.

4.3.2 Spatial autocorrelation between urbanization and NH_3-N

From the distribution relationship between urbanization and NH_3-N (Figure 6), it can be seen that the H-H group mainly centered on areas along the Jiangnan Canal in Wuxi and Changzhou's urban section and the Liangxi River in Wuxi's urban section, where the impact on river water environment from urban pollution is the greatest.

The L-H group is dispersed in the center of Wuxi and its surroundings, which are watershed areas between the Liangxi River and Zhihu Port, the Taihu coast of Binhu District, the

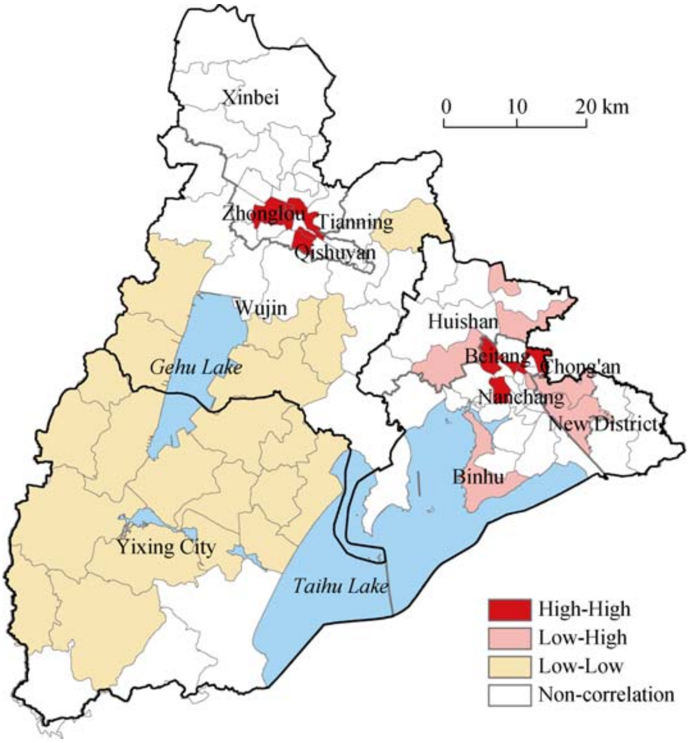

Figure 5 Spatial autocorrelation between urbanization and TP

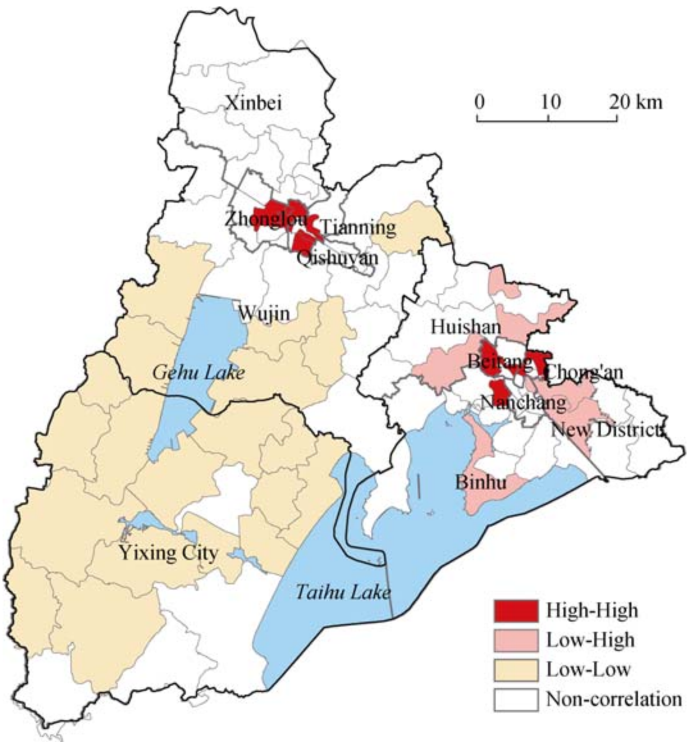

Figure 6 Spatial autocorrelation between urbanization and NH_3-N

drainage basin of Bodu Port, the west side of the Xicheng Canal, and the east side of the Wumu Canal. There is a negative correlation between the proportion of non-agricultural population and NH_3-N in these regions; that is, a lower rate of urbanization correlates to higher water pollution discharge.

The L-L group mainly concentrates on rural areas where the proportion of non-agricultural population is lower, and the river water pollution load is lighter from urban pollution, which cover the west side of Gehu Lake, large areas between Gehu Lake and Taihu Lake, and the Lihe River network.

The spatial autocorrelation between non-agricultural population and NH_3-N is not significant in other regions.

4.3.3 Spatial autocorrelation between urbanization and TN

From the distribution relationship between urbanization and TN (Figure 7), it can be seen that the H-H group is mainly centered on urban areas where the impact on river water pollution from urban pollution is the heaviest.

The L-H group is mainly dispersed in suburban areas of Wuxi City. There was a negative correlation between the proportion of non-agricultural population and TN in these regions; that is, a lower rate of urbanization brings higher impacts on the water environment.

The L-L group is centered on the vast rural areas of Wuxi and Changzhou City, where the proportion of the non-agricultural population is lower and the river water pollution load is lighter from urban pollution.

The spatial autocorrelation between non-agricultural population and TN is not significant in other regions.

As we have seen, there are few differences among the distributions of spatial autocorrelations between urbanization rate and TN, NH_3-N, and TP. To sum up, the H-H areas are mainly located in downtown areas. L-H areas are mainly concentrated around the downtown areas, in new urban areas or suburban areas. L-L areas are mainly found in the vast rural areas.

4.4 Distribution of river water quality classification

4.4.1 Classification

From the six times water quality monitoring occurrences for 84 sites in 2007, we get the average value of four water quality parameters, and their character at each of the monitoring sections is listed in Table 2.

According to the average concentration of each water quality parameters at the sampling sites, five categories are classified (Table 3). Those are, Category II, 2 sites, mainly applies to water source protection areas for centralized drinking water supplies, habitat for rare aquatic, spawning and feeding field for larvae of fish and shrimps. Category III, 6 sites, applies to water source protection areas for centralized drinking water supplies, sanctuaries for common species of fish, and swimming zones. Water in this classification can only enter the water supply after a series of physical, chemical, and biological treatments. Category IV, 27 sites, applies to water bodies for general industrial use and recreational waters in which there is no direct contact of the human body with the water. Water in this category is polluted and requires complex treatment before being used for agricultural irrigation or industrial uses

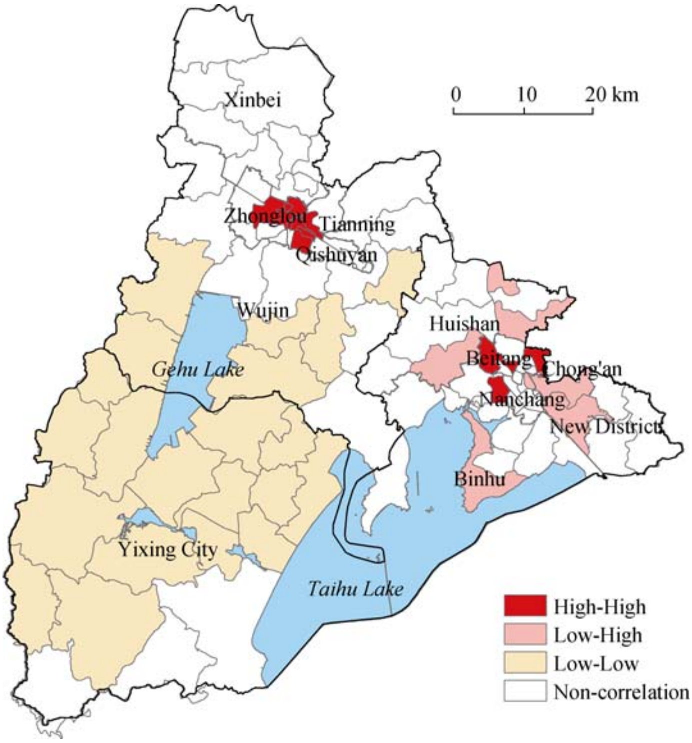

Figure 7 Spatial autocorrelation between urbanization and TN

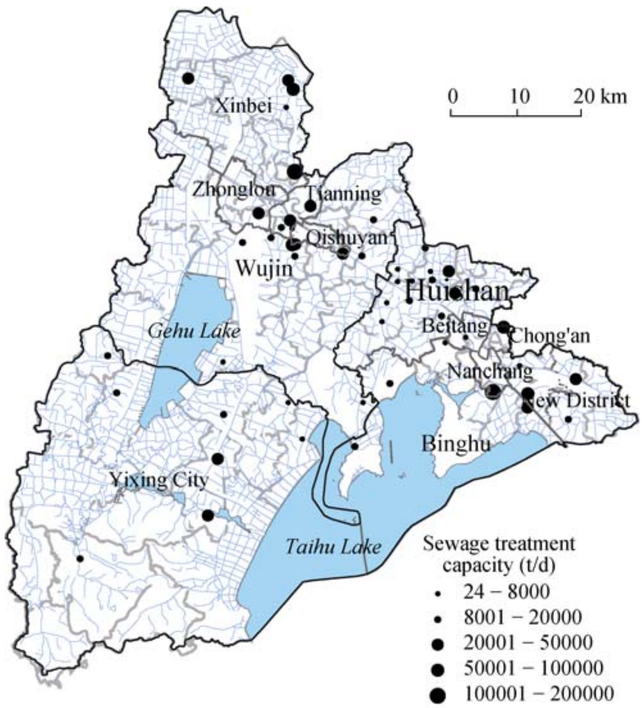

Figure 8 Sewage treatment plant distribution and capacity

Table 2 Descriptive statistics of water quality parameters concentration

Indexes	Sample number	Minimum	Maximum	Mean	Variance
COD	84	13.90	51.04	27.81	83.58
NH_3-N	84	0.18	6.59	1.90	1.29
TN	84	1.53	10.01	4.87	3.22
TP	84	0.07	1.53	0.30	0.04

Table 3 Distribution of water quality type in 2007

Regions	Water quality type					
	II	III	IV	V	V+	Total
Downtown areas	0	1	3	7	10	21
Suburban areas	1	5	11	3	10	30
Rural areas	1	0	13	11	8	33
Total	2	6	27	21	28	84

Note: downtown areas include Tianning District, Qishuyan District and Zhonglou District in Changzhou City, Beitang District, Chong'an District and Nanchang District in Wuxi city. Suburban areas include Xinbei District, five townships in Wujin District nearby downtown of Changzhou City, Huishan District, Binhu District, and New District in Wuxi City. Rural areas include the other towns of Wujin District and Yixing City.

and cannot be used for the food or textile industries, which need a higher quality of water. Category V, 21 sites, applies to water bodies for agricultural use and for general landscape requirements. It is seriously polluted water. Category V+, 28 sites, is commonly used by government reporting agencies to indicate water quality worse than the lowest national standard. In other words, it is used where water quality results far exceed the criteria set for classifying water as Category V.

4.4.2 Distribution

Overlay analysis of river water quality data monitored show that 90.5% is worse than Category Ⅳ, illustrating that a significant amount of water has been polluted during rapid urbanization. The worst water quality is densely distributed in rural areas, for example, Yixing City contributed 14.3% and Wujin District 23.8%. Moreover, the next largest proportion, 28.6%, is distributed in the suburbs, such as Xinbei District with 4.8%, Huishan District 8.3%, Binhu District 4.8%, New District 4.7% and the other areas of Wujin District 6.0%. In contrast, water quality in the downtown areas of Wuxi City and Changzhou City is better, with proportions of 23.8%.

In general, it is shown that water quality is best in downtown area, the suburban next, and the rural worst. From a regional perspective, downtown areas of Changzhou City have best water quality, due to locating in watershed upstream, however, the downtown of Wuxi City has worse water quality situating in downstream of Beijing-Hangzhou Canal, affected by pollution from Changzhou City. As a suburban area, Xinbei District has better water quality which is due to the rivers locating in the watershed upstream, not affected by other water pollution. Located in rivers' downstream, Wujin and Huishan districts have worse water quality, which is easily influenced by downtown of Changzhou City. There are two reasons for poor water quality in the rural, one of which is the trans-boundary water pollution in Wujin District away from the center of Changzhou City; the other is the existing weak water environment regulation.

4.4.3 Sewage treatment plant distribution and treatment capacity

The study area has 52 sewage treatment plants with a processing capacity up to 100.19×10^4 tons per day (Figure 8 and Table 4). Downtown areas have 9 sewage treatment plants, including 4 in Tianning District, the rest of District 1 plant. The sewage treatment capacity is 37.98×10^4 tons daily, Changzhou of which accounts for 25.39%, Wuxi of which accounts for 71.61%. The suburban areas have 35 sewage treatment plants, most of which were located in Huishan District of Wuxi and Wujin District of Changzhou. The sewage treatment capacity is 56.99×10^4 tons daily. However, the rural areas only have 8 sewage treatment plants, which daily process sewage 5.22×10^4 tons. Based on processing capacity per square kilometer, downtown areas have the strongest ability for 1715 tons per day, followed by the suburban of 198 tons per day and the rural lowest of 26 tons per day.

Table 4 The scales of sewage treatment plants in each region

Regions	Count	Actual treatment capacity(t/d)	Design treatment capacity(t/d)	Loading rate (%)
Downtown of Changzhou	6	96439	163000	59.17
Wujin District	9	111000	180000	61.67
Xinbei District	5	244200	325000	75.14
Downtown of Wuxi	3	283400	300720	94.24
Huishan District	13	81170	169000	48.03
Binhu District	3	48375	75500	64.07
New District	4	85145	140024	60.81
Yixing City	8	52162	130000	40.12
Total	52	1001892	1483244	67.55

Overall, the water quality of H-H areas is the best, the L-H areas second, and the L-L area is the worst (see Table 5). The distribution of water quality classification is in contrast to that of water pollution discharge, illustrating the effects of urbanization on water quality. That is to say, the urban areas have the highest urbanization and highest pollution discharge rates, but best water quality. Mainly because of the growing investment in sewage treatment capacity, and with the increase of environmental management and stronger environmental protection, water treatment ratio in these areas is the highest. Moreover, by implementing the national policy to "suppress the secondary industry and develop the tertiary industry," polluting enterprises were encouraged to relocate from the downtown to suburbs (including development zones) and rural areas, reducing river water pollution pressure to a certain degree.

Table 5 Different distribution of index in three type regions

Regions	Urbanization(%)	Pollution emissions (T)				Water quality (%)
		COD	NH_3-N	TN	TP	Ⅳ and above Ⅳ
Downtown areas	85.08	4204.89	619.37	963.05	68.1	23.8
Suburban areas	61.97	690.62	107.24	159.61	11.54	28.6
Rural areas	30.17	190.55	32.00	44.08	3.32	38.1

The suburbs have lower urbanization than the downtown areas, but higher pollution and worse water quality. The reasons are that during rapid urban development and expansion, urban population growth increases the total amount of sewage discharge, and urban expansion is often far beyond the expected speed and scale of urban development and environmental planning. Pollution treatment facilities cannot keep up with expansion, reducing the efficiency of sewage treatment and, ultimately, pollution discharges are greater. When urban industrial enterprises migrate into these areas, the combined effects of industrial pollution and lack of sewage treatment facilities cause water quality to deteriorate.

The rural areas have the lowest rates of urbanization and lowest pollution rates, but the worst water quality. The rural areas have less urban population and less urban sewage, however, mainly affected by upstream pollution, and lagging sewage treatment facilities and poor environmental protection consciousness, rivers have environmental capacity constraints and there is weak environmental remediation, so rural areas can experience the most serious water quality deterioration. The shift to rural areas by urban and suburban polluting enterprises can be one of the most important reasons for deteriorating river water quality.

5 Conclusions

This paper investigates the spatial variation of river water pollution by analyzing data from water environment pollution discharge and water quality of 84 monitoring sections in 2007, and analyzes the distribution of urbanization by using the ratio of non-agricultural population to total population in the study area of the Taihu Lake Basin in 2007. The emphasis is on exploring the correlation between urbanization and water pollution by applying the GeoDa bivariate spatial autocorrelation model.

The results indicate that the impact of human activities is positively correlated with the decline in water quality, confirming the work of Wang *et al*. (2008). In addition to the Taihu Lake region, other cities or regions like Taejon (South Korea), Rome (Italy), Philadelphia (USA), and Mexico City (Mexico) also face challenging water quality management problems due to urbanization, population, and industrialization (Graniel *et al*., 1997; Chan, 2001; Interlandi and Crockett, 2003; Nedeau *et al*., 2003; Mancini *et al*., 2005). In many developing countries, economic development and industrialization often have a higher priority than environmental protection. As a result of ineffective environmental management, lagging environmental facilities, and poor environmental consciousness of inhabitants, industrial, domestic, and agricultural pollutants have been discharged directly into rivers without any treatment, leading to even worse surface water quality conditions during rapid urbanization progress. The results of this study also indicate that river water quality in urban areas is the best among the Taihu Lake Basin, followed by suburban areas, while the condition in rural areas is serious. In spite of improvements in recent years, increasing pollution has resulted from the addition of untreated integrated domestic wastewater and non-point pollution sources to waterways and contributed to worsening water conditions in rural and suburban areas (Wang *et al*., 2008). The capacity for integrated domestic wastewater treatment has not increased along with the increasing volumes of discharge. For instance, there are 97 townships in the study area, but only 38 have wastewater treatment plants, and the overall sewage treatment rate in the study area is only 67.6%. Thus, integrated domestic wastewater treatment has been the dominant issue in water resource management in urban areas. Therefore, urban development planning committees in rural areas should gradually resolve the issue of pollution control lagging behind urbanization rates and urban development, while actively promoting the process of urban development in the region. Priority should be given to construction of centralized sewage treatment facilities and associated pipeline network coverage in the following three areas: 1) Nanchang District, Chong'an District, Beitang District, Binhu District, New District in Wuxi, Zhonglou District, Tianning District, and Hutang Town of Wujin District in Changzhou. 2) The key central towns located along the Shanghai-Nanjing highway and on both sides of the main branch of the Lihe River. 3) Regions along the Lihe River in Yixing City and tributaries connected with it.

Based on the findings, it is suggested to make both water quality and urban development sustainable, the population and industries of urban areas should be continuously redistributed to suburban and rural areas. More measures such as environmental planning, total discharge control of pollutants, and effluent charges should be taken to improve the surface water quality and prevent the increase of pollution in urban areas. Because water resources are mainly distributed in suburban and rural areas, the emphasis on water treatment and protection should be expanded gradually from downtown to suburban and rural areas. Urban surface water quality should be maintained or improved, but water treatment in suburban and rural areas should be the focus on local government as a way to improve overall water quality in the future. Local officials must make the infrastructure and the environmental protection facilities self-contained in suburban and rural areas. In addition, city officials should strengthen the control of pollution sources such as sanitary sewage, municipal drainage, and tertiary industry wastewater. New technologies should be used to increase the capacity of integrated domestic wastewater treatment, and control of non-point pollution sources should be fully implemented.

Although the findings for coordination of regional urban development and water environment conditions are significant, it is not possible to control water pollution simply by building more effective sewage treatment facilities. To promote coordinated and healthy development of urban development and the water environment, some measures are needed to establishing a comprehensive legal framework for pollution reduction, transmitting rational and moderate consumption patterns, strengthening environmental planning and management during urban development, and so on. Additionally, the indicator system used in this research is relatively simple, due to data limitations, and can be further improved in future studies. Urbanization could be characterized by expanding land scale and economic and social factors, not just by population. Simultaneously, water quality could be characterized by accessibility of the water body and landscape features, making the research more relevant.

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