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Temporal variations of surface water quality in urban, suburban and rural areas during rapid urbanization in Shanghai, China

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An integrated pollution index documents the deterioration of water quality in greater Shanghai, recently most serious in rural sections.

Abstract

As the economic and financial center of China, Shanghai has experienced an extensive urban expansion since the early 1980s, with an attendant cost in environmental degradation. We use an integrated pollution index to study the temporal variations of surface water quality in urban, suburban and rural areas between 1982 and 2005. Data on monitored cross-sections were collected from the Shanghai Environmental Monitoring Center. The results indicated that the spatial pattern of surface water quality was determined by the level of urbanization. Surface water qualities in urban and suburban areas were improved by strengthening the environmental policies and management, but were worsening in rural areas. The relationship between economic growth and surface water quality in Shanghai showed an inversed-*U*-shaped curve, which reflected a similar pattern in most developed countries. This research suggests that decision makers and city officials should be more aware of the recent pollution increases in Shanghai.
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Keywords: Temporal variations; Surface water quality; Urbanization; Shanghai

1. Introduction

Since 1979 China has been the world's fastest growing economy. But rapid growth has strained China's water resources. The Huai, Hai and Huang (Yellow) River basins supply just under half the country's population, yet the area accounts for less than 8% of national water resources, and more than 70% of the water is polluted (United Nations Development Programme, 2006).

Shanghai is the largest city with the highest level of urbanization in China. Taking the ratio of non-agricultural population to the total population as the evaluative standard for the level of urbanization, it was 84.5% at the end of 2005, while the national level was only 42.9%. As the economic center, since the late 1980s, Shanghai's economy has maintained a high-speed growth, with its annual Gross Domestic Product (GDP) increasing at about 10%. However, it is also listed by the United Nations (Zheng, 2001) as one of six cities with serious deficiency of water resources of the 21st century, with potable water amounting to only 20% of total surface water resources. In average water resources per capita, Shanghai stands at 40% of the national average in China and 10% of the global average (Zheng, 2001). In addition, the water quality grade of the Huangpu River, which provides over 80% of Shanghai's water supply, varies between grade III and over grade V, whereas over grade V is the worst score in the national standard for water quality in China, and only water

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with a grade lower than III is potable (Shanghai Environmental Protection Bureau, 1983–2006). Thus, the use of water resources is strongly limited by the water quality. Sustainable development in terms of water quality becomes the chief focus in the ecology of urbanization.

Many research studies have shown a close relationship between water quality and urban development. For example, LeBlanc et al. (1997) found that land-use intensification increased water temperature. Fisher et al. (2000) also discovered that land use had impacts on the quality of surface water. Feng et al. (2004) characterized rapid urbanization and recent coastal wetland reclamation as main contributors to the Yangtze River's heavy metal contamination. Tang et al. (2005) indicated that urban expansion was a major driving force in increasing non-point source pollution. Several studies on water quality issues in Shanghai have been weakened by limitations. For example, the classifications of water quality used by Ren et al. (2003) could not reflect actual water quality, and Yin et al. (2005) only used one year's water quality data to investigate the relationship between spatial patterns of urban land-use and water quality.

Since many environmental data are sensitive and not available to the general public, only a few long-term studies on various spatial scales have been published. In this paper, an integrated pollution index was used to characterize spatial and temporal variations of surface water quality during Shanghai's rapid urbanization between 1982 and 2005. The results of this study may help decision makers and city officials to alleviate water quality issues in the course of Shanghai's development as a ''global city''.

2. Methods

2.1. Study area

Shanghai is located on the coast of the East China Sea and at the estuary of the Yangtze River. The total area of the Municipality of Shanghai is 6340.5 km^2, of which 121 km^2 is water (Fig. 1).

To explore the consequences of urbanization, we classified Shanghai into urban, suburban and rural areas. The general descriptions of the three spatial areas are shown in Table 1.

Like most cities in China, Shanghai is overbounded in its administrative territory. Especially after 1992, Shanghai began a rapid developing phase with an annual GDP increment of 12.4% (Shanghai Statistical Bureau, 1983–2006), and its administrative territories were redivided continually. Though the urban territory remained unchanged, the administrative territory of suburban areas expanded from four districts (Pudong New Area, Minhang, Baoshan and Jiading) in 1992 to nine districts (Pudong New Area, Minhang, Baoshan, Jiading, Nanhui, Fengxian, Songjiang, Jinshan and Qingpu) in 2005, with a total increase in area 1624.2 km^2–4865.6 km^2. Further, the administrative territory of the rural areas, whose total area was 4426.8 km^2 in 1992, shrunk from six counties (Nanhui, Fengxian, Songjiang, Jinshan, Qingpu, and Chongming) to one county (Chongming) in 2005, with a total area of just 1185.5 km^2. To date, only Chongming is counted as a rural area, but the other five administrative areas still contain substantial rural land and a number of rural residents who continue to farm for their livelihood. Moreover, the urban areas are located in the centre of city. The suburban areas are next to them, and the rural areas are farthest away. In this study, to characterize spatial and temporal variations of surface water quality, the division of spatial areas is based on the administrative territories of 1992.

According to the three censuses of China of 1982, 1990 and 2000, the average level of urbanization for urban areas was 100% all along. The average urbanization level for suburban areas increased from 31.7% in 1982 to 44.0% in 1990, while for rural areas, it rose from 10.0% to 14.0%. At the end of 2000, suburban areas were in the process of middle-development, with an average urbanization level of 58.4%. But rural areas were at the stage of early-development, with an average urbanization level of 29.8% (Table 2).

2.2. Analytical methods

Systematic monitoring on water pollution in Shanghai was started in 1982. For this paper, the study has been carried out over a period of 24 years (1982–2005). Surface rivers and lakes have been polluted mainly by integrated organic pollution, so we use nine water parameters that include permanganate value, chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), Kjeldahl nitrogen (KN), total phosphorus (TP), total nitrogen (TN), total mercury (THg), volatile phenol (VP) and oils to calculate the integrated pollution index for the three areas. The larger the integrated pollution index is, the worse the surface water quality. Data from 73 monitored cross-sections were provided by the Shanghai Environmental Monitoring Center (Shanghai Environmental Protection Bureau, 1983–2006). Locations of monitored cross-sections in three spatial areas are shown in Fig. 1.

Based on the ''Environmental Quality Standards for Surface Water'' of China (State Environmental Protection Administration, 2002), the surface water environment is divided into five grades, and each grade has its corresponding standard value. In Shanghai, surface water quality has been improved in recent years, but according to the comprehensive evaluation of 2005 on 16 main rivers with 612.9 km length, 68.3% of total length was still grade V and over grade V (Shanghai Water Authority, 2005). In order to compare spatial and temporal variations of the three regions, we use the value of grade V as surface water standard concentration for all monitored cross-sections.

We use the following formula to calculate the surface water quality.

$$\mathrm{PI} = \frac{1}{n}\sum_{i=1}^{n}\frac{C_i}{C_o} \quad (i = 1, 2 \ldots, n) \tag{1}$$

where PI is the integrated pollution index; C_i is the actual surface water concentration, mg/l; C_o is the value of surface water standard concentration, mg/l (Table 3); and n is the number of monitoring parameters.

3. Results

3.1. Spatial patterns according to the integrated pollution index

The values on the integrated pollution index spatially showed that surface water pollution in urban areas was the most severe, followed by suburban areas, and with rural areas relatively better (Fig. 2). Except for 1982, the integrated pollution index for urban areas was far above the standard value. And it was 3 times higher than the standard value during 1986–2000, which was also the period with the highest economic growth. From 1988 to 1999 (except for 1989, 1991, 1992 and 1998), it was a little above the standard value in suburban areas. But for rural areas, it was actually below the standard value. In sum, the contribution rates of the pollution loads from the three spatial regions were mainly determined by urban water pollution.

Specifically, the spatial variations in the level of urbanization were consistent with the variations on the integrated pollution index. The higher the urbanization level was, the worse the surface water quality (Fig. 3).

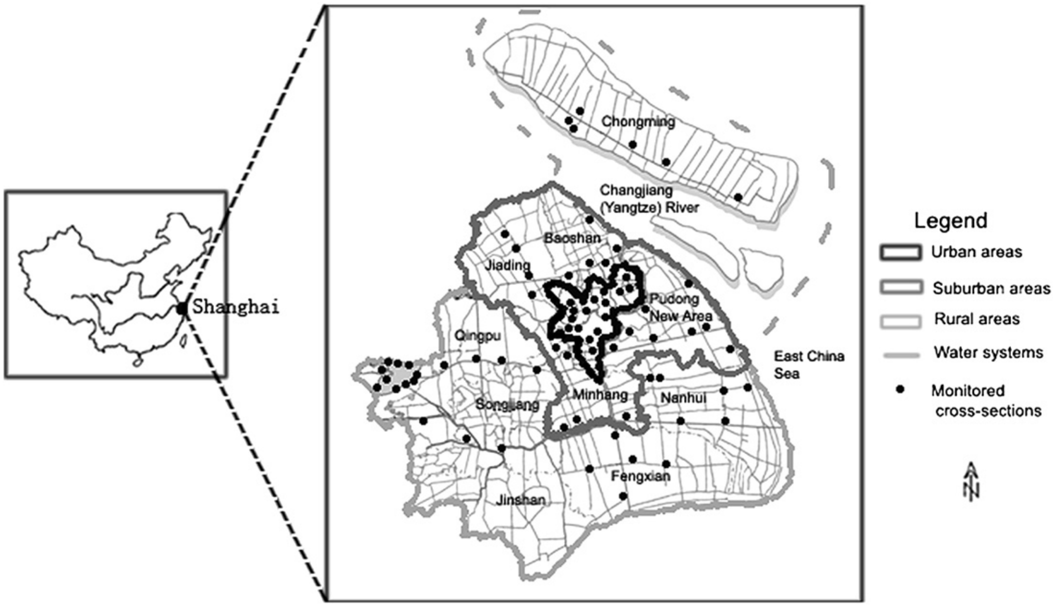

Fig. 1. Locations of Shanghai administrative areas and monitored cross-sections.

3.2. Yearly changes in the integrated pollution index

Fig. 4a shows that the integrated pollution index for urban areas increased in the first period of the 1980's and then decreased in the first period of the 1990's. With respect to suburban areas, the index increased in the first period of the 1980's, but decreased in the middle of 1990's (Fig. 4b). The annual variations in urban and suburban areas show an inverted-*U*-shaped curve which reflects a developing phase of "pollution first, treatment after". The inverted-*U*-shaped curve for the urban areas is steeper than that of the suburban areas. The critical turning point shows a tendency for the integrated pollution index to decrease in 1993 for urban areas and around 1995 for suburban areas. In rural areas, however, the integrated pollution index has undulated in its range and risen significantly in recent years (Fig. 4c).

3.3. Surface water quality shows an inverted-U-shaped Environmental Kuznets Curve with fast economical growth

At the beginning of the 1990s, the hypothesis of the Environmental Kuznets Curve (EKC) was proposed, which indicates an inverted-*U*-shaped relationship between environmental degradation (pollution or deforestation) and per capita income (Grossman and Krueger, 1991). Then many scholars such as Panayotou (1997), De Bruyn et al. (1998), Sun (1999), and Fatma and Osman (2001) discussed and validated the EKC theory by using different countries and regional data. All studies indicated that most developed countries are already in the right half part of the inverted-*U*-shaped curve. Similar research has been performed in recent years in China. To a larger extent, China is still in the left half part of the inverted-*U*-shaped curve, except for the most economically developed cities, like Beijing (Wu et al., 2002). In Shanghai, the relationship between the integrated pollution index and GDP per capita also shows an inverted-*U*-shaped curve (Fig. 5).

Based on the estimate from Grossman and Krueger (1995) and the study for the cross-sectional data in different countries and regions, the air and water pollutants will increase before GDP per capita achieves $5000–$8000 (in 1985 purchasing power parity US$) (Zhao et al., 2005). The environmental quality will improve gradually when this income level is surpassed. Shanghai reached the turning point when GDP per capita was about $6442.9 in 1995. The turning point time for Shanghai is in the range between $5000 and $8000. Again,

Table 1
General description of urban, suburban and rural areas in 2005

Region	District	Area[a]	Population density[b]
Urban areas	Huangpu, Nanshi, Luwan, Xuhui, Changning, Jing'an, Putuo, Zhabei, Hongkou, Yangpu	289.4	21,283
Suburban areas	Pudong New Area, Minhang, Baoshan, Jiading	1624.2	2469
Rural areas	Nanhui, Fengxian, Songjiang, Jinshan, Qingpu, Chongming	4426.8	775

All data were taken from Shanghai Statistical Bureau (1983–2006).
[a] Area in km^2.
[b] Population density in per/km^2.

Table 2
The levels of urbanization for urban, suburban and rural areas in different years

Year	The levels of urbanization[a]				
	Urban areas	Suburban areas		Rural areas	
		Average	Range	Average	Range
1982	100	31.7	18.8–43.8	10.0	4.0–16.5
1990	100	44.0	21.4–54.8	14.0	7.4–24.1
2000	100	58.4	37.0–68.8	29.8	18.2–39.8

All data were taken from Shanghai Census Bureau (2005).
[a] All units in percent (%).

Table 3
Values of surface water standard concentration for five grades

Parameter		Grade[a]				
		I	II	III	IV	V
Permanganate value	≤	2	4	6	10	15
Chemical oxygen demand (COD)	≤	15	15	20	30	40
Biochemical oxygen demand (BOD_5)	≤	3	3	4	6	10
Kjeldahl nitrogen (KN)	≤	0.15	0.5	1.0	1.5	2.0
Total phosphorus (TP)	≤	0.02	0.1	0.2	0.3	0.4
Total nitrogen (TN)	≤	0.2	0.5	1.0	1.5	2.0
Total mercury (THg)	≤	0.00005	0.00005	0.0001	0.001	0.001
Volatile phenol (VP)	≤	0.002	0.002	0.005	0.01	0.1
Oils	≤	0.05	0.05	0.05	0.5	1.0

All data were taken from Environmental Quality Standards for Surface Water of China (State Environmental Protection Administration, 2002).
[a] All units in mg/l.

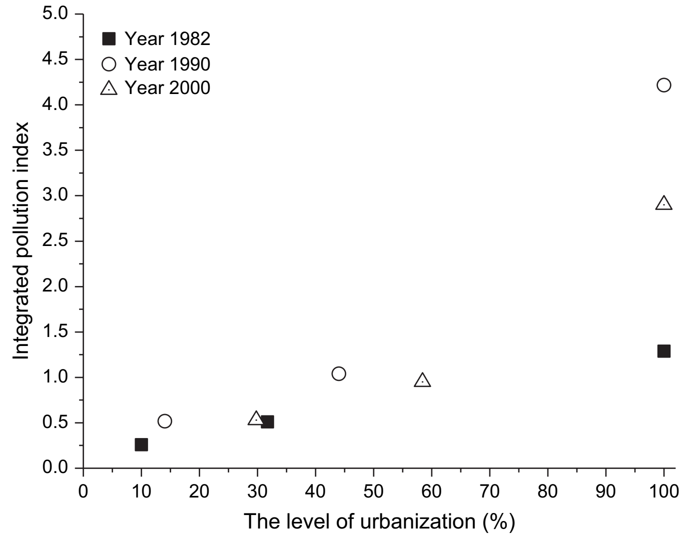

Fig. 3. Relation between integrated pollution index and the level of urbanization for urban, suburban and rural areas in 1982, 1990 and 2000.

the estimated relationship turns back up again at $18,811.9 with the rising of the economy in 2004.

4. Discussion

4.1. Impacts of the level of urbanizations on spatial patterns of surface water quality

The United Kingdom achieved a high urbanization as early as 1891, which illustrating that industrialization greatly accelerated the development of the cities and led to the movement of urbanization. It is also the case for such developed countries as the United States, France, Canada and Japan. Shanghai's industrial enterprises have been concentrated in urban areas since its establishment, as in other developed countries. Urban areas had 55.9% of the total enterprises and generated 70.3% of the total industrial output in 1983 (Shanghai Statistical Bureau, 1983–2006). Later on, as a result of industrial policy shift, industrial sectors in urban areas were moved out to suburban and rural areas (Hou and Sun, 1999). However, the suburban ratio of industrial output was higher than that of rural areas from 1982 to 2005.

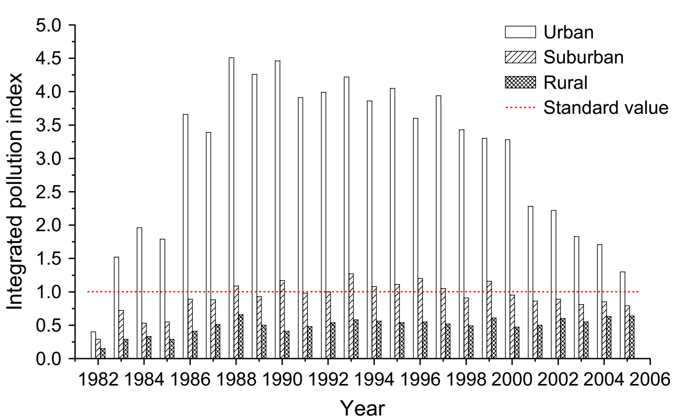

Fig. 2. Spatial pattern of integrated pollution index in urban, suburban and rural areas.

The intensity of urbanization may also be mainly measured by population density. In Shanghai 51% of the population resided in urban areas that only occupied 4.6% of the whole land area in the year 1983, and the figure began to decrease after 1994 (Shanghai Statistical Bureau, 1983–2006). The suburban areas are heavily influenced by the urbanization of urban areas. The majority of the population from urban areas' migration and the external floating population converge in the Pudong New Area, Minhang, Baoshan and Jiading. As a result the population density in suburban areas increased from 1407 person/km^2 in 1983 to 2469 person/km^2 in 2005, while the rural areas were at the lowest level in 2005, just 775 persons/km^2 (Shanghai Statistical Bureau, 1983–2006). The overall population density continuously maintains spatial pattern relatively similar to the integrated pollution index (Fig. 6). Thus, the impacts of human activities are positively correlated with the decline in water quality.

The spatial patterns in the level of industrialization and population density cause the differences in the discharge volumes of industrial and integrated domestic wastewater, producing diverse impacts on surface water. Since industrial wastewater treatment has traditionally been emphasized in Shanghai, the city's technology and equipment are quite mature. From 1991 to 2004, the capacity of industrial wastewater treatment was enhanced from 65.3% to 96.3% (Shanghai Statistical Bureau, 1983–2006). Since 1996, the chief components of wastewater have shifted from industrial wastewater to integrated domestic wastewater. But the capacity of integrated domestic wastewater treatment has not been improved along with the increasing volumes of discharge. For instance, the wastewater treating plants could only treat 1.29 hundred million tons in 1996, while the discharge volumes achieved 11.44 hundred million tons (Shanghai Statistical Bureau, 1983–2006). Up until now, integrated domestic wastewater treatment has been the dominant issue in water environment management, particularly in urban areas. Besides Shanghai, other cities or regions like

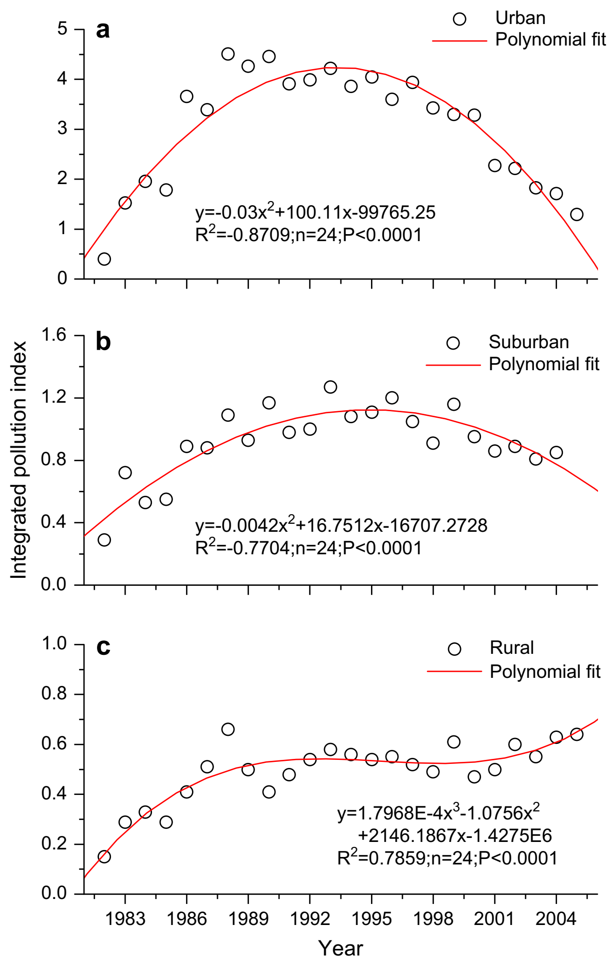

Fig. 4. a, b, & c. Polynomial fit of integrated pollution index. a is for urban areas; b is for suburban areas; and c is for rural areas.

Taejon (South Korea), Rome (Italy), Philadelphia (USA), Michigan (USA) and Mexico City (Mexico) are also facing some of the most 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).

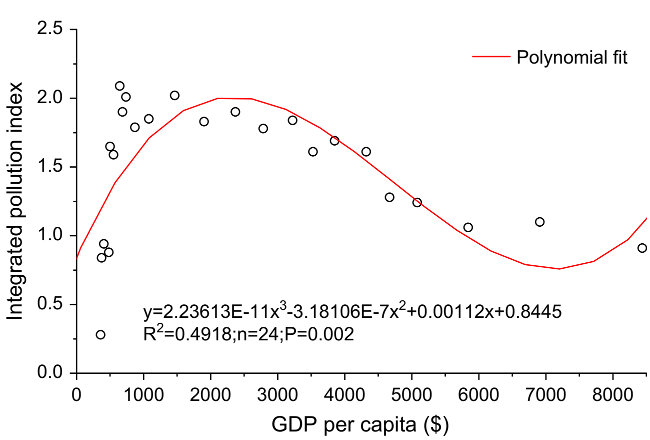

Fig. 5. Relation between GDP per capita and integrated pollution index in Shanghai, 1982–2005 (in 1985 purchasing power parity, US$).

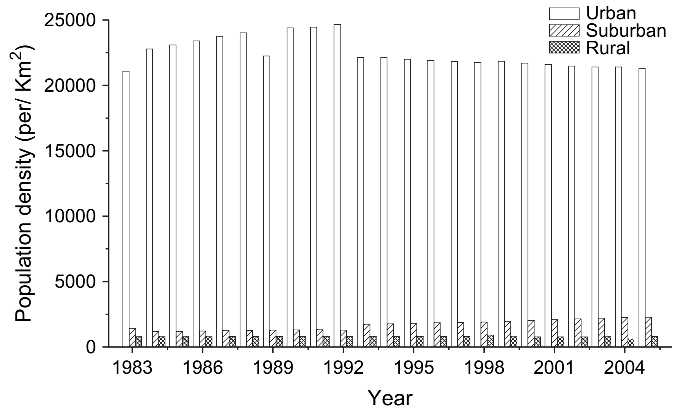

Fig. 6. Population density in Shanghai, by regions, 1983-2005.

4.2. Impacts of economical development and environmental policies on the annual changes in surface water quality

On a historic scale, with rapid urbanization and recognizing more footprints worldwide, people in New York City began implementing a series of programs to reduce the susceptibility of the surface water supply to contamination from a variety of sources, in a program that included effectively expanding its total land holdings in the watershed, so that more than 105,000 acres are now forever protected from development (New York City Department of Environmental Protection, 1997–2005). The cleanup of the UK water environment also represents a highly significant act of environmental improvement, along with that experienced within other industrially developed parts of the world such as Germany (Neal et al., 2000).

Learning from developed countries, local regulations and rules such as the Rule of Shanghai Huangpu River on Protection of Upriver Water Resources (1985), Provisions on Effluent Charges and Fines of Shanghai (1984), and the Three-year Environmental Action Plan (2000–2002; 2003–2005; 2006–2008) were all propelling forces toward the decrease in water pollution. In addition, from 1978 to 1991, Shanghai got into the fast developing phase with an annual GDP increment of 8.1%, due to the reform and opening policy of China. After 1992, the economy increased with higher speed, whose annual GDP increment achieved 12.4%. Thus, the GDP per capita grew from $849.7 in 1978 to $22,956.5 in 2005, while the nation was at only $4742.9 (in 1985 purchasing power parity US$). The environmental investment also increased while maintaining growth in GDP. It rose from $0.26 billion in 1991 to $33,614.88 billion in 2005 (in 1985 purchasing power parity US$), which reached a 3.07% GDP in Shanghai (Shanghai Statistical Bureau, 1983–2006). Accordingly, the capacity of wastewater treatment was increased by building more wastewater treatment plants and improving the technology.

Those political and economic activities have led to gradual improvements in the surface water quality in urban and suburban areas in the 1990's. Between 1991 and 1998, 12,000 enterprises along with 400,000 households were relocated from urban areas to suburban and rural areas as the result of industrial restructuring, new developments for housing, and reconstruction of urban areas (Yusuf and Wu, 2002). The proportion of industrial output in urban areas dropped from 70.3% in 1983 to 11.8% in 2005 (Shanghai Statistical Bureau, 1983–2006). These data suggested that many pollution sources had been taken away from urban areas. Re-distribution of population and adjustment of industrial structure put even heavier burdens on the water environment of suburban areas. Thus, the time when the critical turning point appeared was two years later for suburban areas than for urban areas. In rural areas, industrial manufacturers amounted to 14,047 in 1990; with 3197 of them engaged in heavy polluting industries that included galvanization, chemical production, printing, paper production, and brewing (He, 1997). With the increase in the standard of living for farmers, the volumes of domestic wastewater increased significantly. In addition, the use of chemical fertilizer had increased more than 20%, compared to that of the 1970's. At the same time, organic pollution increased with the poultry refuse overflow (He, 1997). Due to ineffective environmental management, lagging environmental facilities and poor environmental consciousness of inhabitants, industrial, domestic and agricultural pollution were discharged directly into rivers without any treatment, leading to even worse surface water quality conditions in rural areas.

However, as happens in many developing countries, economic development and industrialization often have a higher priority than environmental protection (Shen et al., 2002). In spite of improvements in recent years, increasing pollution has resulted from the addition of untreated integrated domestic wastewater and non-pollution sources to waterways, as well as to worsening water conditions in rural areas. At the national level, rising energy consumption has been blamed for an alarming rise in China's key pollution indices in the first half year of 2006 despite the government's environmental targets and control efforts (State Environmental Protection Administration, 2006). A World Bank report indicated that economic losses caused by environmental pollution in China ranged from 3 to 8% of GDP (World Bank, 1997). It suggests that local governments and central departments must raise awareness of the responsibility and urgency of environmental protection with the rising economy, especially in viewing of the environmental worsening in recent years.

5. Conclusion

This paper investigates the spatial and temporal variations of integrated pollution index in surface water quality by analyzing the data from 73 monitored cross-sections of Shanghai between 1982 and 2005. The results indicated that surface water quality was worst in urban areas, next in suburban areas and least serious in rural areas, comparatively. As a result of strengthened environmental policies and management with economic growth, surface water quality in urban and suburban areas has shown some improvement; however, the water environment in rural areas has worsened. As a whole, the relationship between economic growth and surface water quality presents an inverted-*U*-shaped curve. The increase of pollution in recent years has resulted from the contribution of polluted water in rural areas and untreated integrated domestic wastewater.

In order for both water quality and economic development to be sustainable, the results of this paper suggest that the population and industry of urban areas should be continuously re-distributed to suburban and rural areas. More measures such as environmental planning, total discharge control of pollutant, and effluent charges should be taken to improve the surface water quality and prevent the increase of pollution in urban areas.

Since water resources are mainly distributed in suburban and rural areas, the emphasis on water treatment and protection should be expanded from downtown to suburban and rural areas gradually. Suburban surface water quality should be maintained and continue to be improved, but water treatment in rural areas should be the focus of local government as a way to improve overall water quality in Shanghai. 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. Enterprises should begin to recognize the new cyclic economy and take the path of "control while developing". Environmental awareness and community outreach programs should also be implemented.

Acknowledgments

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