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Article

Analysis of the Temporal and Spatial Distribution of Lake and Reservoir Water Quality in China and Changes in Its Relationship with GDP from 2005 to 2010

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Abstract: We analyzed the spatial distribution of lake and reservoir water quality in China, and the trends from 2005 to 2010, based on monitoring data from 28 large Chinese lakes and reservoirs. We used a comprehensive water pollution index (WPI) to describe water quality and also identified the major pollutants. Using GDP data, we analyzed the relationships between economic factors and water quality. We found that although the water quality of large reservoirs is improving or remaining stable, despite economic growth, the water quality of most lakes either did not change or worsened. The outlook is pessimistic, as water quality in most lakes has decreased to Grade V or worse. The water quality was lowest for northern lakes and highest for southern lakes due to a combination of the local industrial structure and lower rainfall in the north. The primary pollutants generally remained stable during the study period. For some lakes, fluoride and volatile phenols became the primary pollutants, indicating more diverse sources of contamination. We divided the 28 bodies of water into four types based on the median WPI and GDP. The dominant combinations were low WPI with low GDP and high WPI with high GDP, as a result of the balance among economic development, the natural environment and environmental policy.

Keywords: aquatic environment; water quality; temporal and spatial distribution; water pollution index; correlation analysis

1. Introduction

Lakes and other water bodies serve as the focus of interactions among various components of the terrestrial system, and in many areas, they are the most important freshwater resources. Lakes play essential roles in maintaining the ecological balance of watersheds, meeting the water needs of residents and preventing flooding. According to *Chinese Lakes* [1], China has 2759 lakes larger than 1.0 km^2, and these lakes cover a total area of more than 91,000 km^2.

After the 1970s, rapid socioeconomic development in and near lake basins has led to intensive human activities that have increasingly damaged the water quality in most lakes, especially in China's densely populated and highly industrialized eastern plains. For example, frequent algal blooms occurred in Chaohu Lake in the late 1980s [2] and in Taihu Lake in nearly every year, especially in 2007 [3], and a continuous algal bloom affected Dianchi Lake in 1998 and 1999 [4]. These events provide clear proof that the water quality of Chinese lakes has become severely degraded. To control water pollution, the Chinese government has implemented many regulations, such as the "Control Program for Water Pollution in Dianchi Lake Basin (2006–2010)" [5], the "Control Program for Water Pollution of Chaohu Lake Basin (2006–2010)" [6] and the "General Planning for Comprehensive Water Treatment in the Taihu Lake Basin" [7]. The government invested 1.278×10^{11} RMB during the period of 2006 to 2010 to control industrial pollution of water, build sewage treatment plants and implement comprehensive regional control of the pollution levels in three major lakes [8]. The water quality in these regions has improved to some extent or has at least not worsened.

However, despite these efforts, the rapid development of China's economy and the implementation of regional development plans, such as the Western China Development Strategy, have caused a continuously decrement of the overall water quality in lakes. Since the announcement of the water environment quality guidelines by the Chinese Ministry of Environmental Protection in 2010, the water quality in eight of the 28 key state-controlled lakes and reservoirs (*i.e.*, water bodies identified and prioritized by China's central government because of their large size and the environmental and socio-economic importance) has degraded to below Grade V: Taihu Lake, Dianchi Lake, Dalai Lake, the Dahuofang Reservoir, Baiyang Lake, the Menlou Reservoir, the Laoshan Reservoir and Dongting Lake. Except the last one, in central China, the other lakes and reservoirs are located in the north, the northeast and the Inner Mongolia-Xinjiang Plateau. Such a level of water quality degradation means that the water is unsafe for human consumption and cannot be used by industry and clearly shows that the scope of China's lake and reservoir pollution problem has expanded far beyond the "three lakes" region, which includes Taihu, Chaohu and Dianchi lakes. In particular, it has begun to affect the northern and northwestern regions, which are characterized by low precipitation (thus, low self-purification capacity), a fragile ecological environment and difficulty in ecological restoration.

Efforts to decrease pollution in Chaohu, Dianchi and Taihu lakes have consumed large amounts of labor, time and economic resources. To reduce the need for such expenditures in other lake and reservoir basins, measures should be taken to avoid damaging water quality in the central and northern regions. In order to understand the problem and prioritize mitigation efforts, it is necessary to comprehensively analyze the temporal and spatial variation of water quality in key Chinese lakes and reservoirs and to determine the relationship between the water pollution characteristics and socioeconomic development. This knowledge will provide scientific guidance to adjust economic development strategies, develop sound strategies for protecting the water environment of Chinese lakes and reservoirs and implement more sustainable socioeconomic development to protect the environment.

In the present study, monitoring data from 2005 to 2010 were used, concerning 24 water quality parameters collected by the Chinese Ministry of Environmental Protection in the 28 key lakes and reservoirs in China. This study period was selected because it represented the longest period during which data were available for all of the investigated key lakes and reservoirs. Moreover, considering the different socioeconomic development conditions in these 28 key lakes and reservoirs, the temporal and spatial variations in water quality and the relation with socioeconomic development was analyzed. The main objective was to identify the temporal distribution of water quality at the national scale and the relationship between economic development and water quality, in order to provide a more scientific basis for developing strategies for the protection and sustainable utilization of Chinese lakes and reservoirs.

2. Data and Methodology

2.1. Data

The utilized dataset includes monitoring data for the 28 key water bodies (Figure 1): 10 freshwater lakes (*i.e.*, where the mineral concentration of lake water is less than 1 g/L), 5 municipal lakes (*i.e.*, lakes located in big and medium-sized city, where the urban development conditions are related to the natural and social functions of the lakes), 10 large reservoirs (*i.e.*, more than 0.1 million cubic meter storage) and 3 large lakes (Chaohu, Taihu and Dianchi). The data were obtained from 262 monitoring sections in these water bodies from 2005 to 2010. The data included the following 24 water quality parameters: water temperature, water level, pH, dissolved oxygen content (DOC), permanganate index (COD_{Mn}), biological oxygen demand (BOD_5, after 5 days of incubation), chemical oxygen demand (COD_{Cr}), NH_4-N (ammonium nitrogen), petroleum compounds (hereafter, "oils"), total nitrogen (TN), total phosphorus (TP), 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. Due to the large amount of data for 2005 and the impossibility of reporting the whole dataset in this paper, Xuanwuhu Lake was selected as the example, and the original data and the calculated results of water pollution index (WPI) and K are shown in the Table A1. Unless otherwise noted, all data were obtained from the Chinese Ministry of Environmental Protection. In each monitoring section the parameters were detected quarterly and the yearly average calculated, in order to be in line with the annual values of GDP. The caption of Figure 1 shows the number of monitoring sections in each lake: if the number of monitoring sections in each lake is more than 3, these sections include estuary, bayou and the central part of the water body; if the number is less than 2, the monitoring sections include only estuary and bayou.

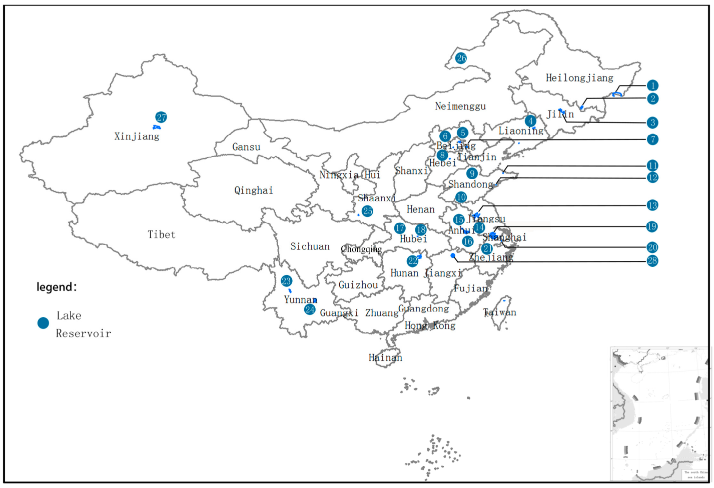

Figure 1. Locations of the key lakes and reservoirs included in the present study. 1. Xingkai Lake (Mishan City, Heilongjiang Province, monitoring data from 3 sections); 2. Jingbo Lake (Mudanjiang City, Heilongjiang Province, 3 sections); 3. Songhua Reservoir (Jilin City, Jilin Province, 5 sections); 4. Dahuofang Reservoir (Fushun City, Liaoning Province, 5 sections); 5. Miyun Reservoir (Miyun County, Beijing City, 1 section); 6. Kunming Lake (Haidian District, Beijing City, 1 section); 7. Yuqiao Reservoir (Ji County, Tianjin City, 3 sections); 8. Baiyang Lake (Baoding City, Hebei Province, 9 sections); 9. Daminghu Lake (Jinan City, Shandong Province, 3 sections); 10. Nansi Lake (Jining City, Shandong Province, 5 sections); 11. Menlou Reservoir (Yantai City, Shandong Province, 2 sections); 12. Laoshan Reservoir (Qingdao City, Shandong Province, 3 sections); 13. Hongze Lake (Huai'an City, Jiangsu Province, 6 sections); 14. Xuanwuhu Lake (Nanjing City, Jiangsu Province, 2 sections); 15. Dongpu Reservoir (Heifei City, Anhui Province, 2 sections); 16. Chaohu Lake (Heifei City, Anhui Province, 24 sections); 17. Danjiangkou Reservoir (Danjiangkou City, Hubei Province, Nanyang City, Henan Province, 4 sections); 18. Donghu Lake (Wuhan City, Hubei Province, 5 sections); 19. Taihu Lake (Shanghai City; Hangzhou City, Jiaxing City, Huzhou City, Pinghu City, Zhejiang Province; Zhenjiang City, Wuxi City, Wujin City, Yixing City, Wujiang City, Danyang City, Changzhou City, Suzhou City, Jintan City, Liyang City, Kunshan City, Taicang City, Changshu City, Jiangyin City, Zhangjiagang City, Tongxiang City, Zhejiang Province; 110 sections); 20. Xihu Lake (Hangzhou City, Zhejiang Province, 3 sections); 21. Qiandao Reservoir (Chun'an County, Zhejiang Province, 3 sections); 22. Dongting Lake (Yueyang City, Yiyang City, Changde City, Jin City, Changsha City, Yuanjiang City, Hunan Province, 12 sections); 23. Erhai Lake (Dali Prefecture, Yunnan Province, 9 sections); 24. Dianchi Lake (Kunming City, Yunnan Province, 18 sections); 25. Shimen Reservoir (Hanzhong City, Shanxi Province, 1 section); 26. Dalai Lake (Manzhouli City, Inner Mongolia Autonomous Region, 2 sections); 27. Bositeng Lake (Bazhou City, Xinjiang Province, 14 sections); 28. Poyang Lake (Jiujiang City, Nanchang City, Jiangxi Province, 4 sections).

2.2. Methodology

2.2.1. Water Quality Assessment

Various methodologies have been developed to assess water quality, including specific applications to Chinese case studies [9]. Shi *et al*. [10] analyzed the temporal and spatial distribution of 4 monitoring sections of Qujiang River using the grey system analysis method, providing a useful method when a lack of data is the main issue. Zhou *et al*. [11] analyzed the trend of water quality in Dianchi Lake adopting wavelet analysis, a method based on a complex calculation and not suitable for a large amount of data. Chang *et al*. [12,13] used fuzzy mathematical analysis, considering uncertainty factors in the water system and applying the linear weighted average method, which could result in some ineffectiveness, homogenization and inaccuracy. Li *et al*. [14] adopted the artificial neural network method for sea water assessment, simulating the interactions of a biological nerve system with the real world and providing a tool that can only categorize water quality, without reflecting its temporal changes. Feng *et al*. [15] assessed groundwater quality using the matter element analysis method, which is easier than the artificial neural network method, but still presents the same limitations. Chen *et al*. [16] applied the analytical hierarchy process method (AHP), a flexible and practical method to combine qualitative and quantitative determination, but showing high subjectivity in the allocation of weights based on the knowledge and experience of the experts. At the international level, in 2007, the Great Lakes Environmental Indicators (GLEI) project was implemented in the U.S. Subsequently, various investigators have related the GLEI indicator to various fields to assess the link between anthropogenic activities and water quality using classification and regression tree analysis (CART) [17], special ecological indices [18], the cumulative stress index [19] and hierarchical partitioning and all-subsets regression analyses [20]. Besides, several predictive models based on input-output [21,22], multivariate statistical techniques [23,24], the three-dimensional hydrodynamic and water quality model [25] and the continuous wavelet time series analysis [12] have been developed to evaluate water quality. However, many of them are not widely used, because of the complicated calculation processes [26]. Index evaluation is simpler and can be effective for analyzing water quality and its trend [27–29]. This approach was used in water quality evaluation for many lakes and rivers, such as the Odzi River [30] and the Suquia River [31]. This approach also allows a flexible comparison of water quality and trends among different water systems and an examination of temporal variation in a given water system [32]. Accordingly, in the present work, a comprehensive water pollution index method and a pollution weight method (based on the proportion of the total pollution) was adopted to evaluate the water quality of lakes in China. Dealing with a large amount of data and trying to reduce the data processing work effectively, the proposed method uses the following equations to calculate the pollution indices [31,33–35]:

$$WPI_i = \sum_{j=1}^{n} \frac{c_j}{c_{j0}} \tag{1}$$

$$WPI = \frac{\sum_{i=1}^{m} WPI_i}{m} \tag{2}$$

where WPI_i denotes the water pollution index for each monitoring section *i*; *j* represents the selected water quality parameters (for parameters 1 to *n*); c_j denotes the measured value for the water quality parameter *j* (unit: except for pH, the others are mg/L); c_{j0} denotes the water quality threshold values for each selected parameter *j* (unit: except for pH, the others are mg/L), according to the Chinese Environmental Quality Standards of Surface Water (GB3838-2002) (Table 1), which requires a classification of water bodies into five classes considering their purpose for use and the protection target (see Table 2) [36]. Each monitoring section of a lake was classified as representing one of these five functional zones, with a specific water use (e.g., to provide drinking water *versus* water for industrial use) and a corresponding minimum water quality class required to support that use.

WPI denotes the comprehensive water quality index for each lake, considering all of the *m* monitoring sections investigated in each lake. High values of WPI indicate high levels of pollution and, thus, low water quality.

Finally, the following equation was used in the proposed approach in order to calculate the pollutant weight [33], which provides an estimation of the contribution of each water quality parameter *j* to the comprehensive pollutant index.

$$K_j = \frac{\sum_{i=1}^{m} WPI_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n} WPI_{ij}} \times 100\% \quad (3)$$

where K_j denotes the total share of all pollutants accounted for by pollutant *j*; *n* denotes the number of pollutants (*i*); and *m* denotes the number of monitoring sections. A pollutant with a higher degree of K is considered the main concern for the investigated lake and should be regarded as a sensitive parameter for the definition of specific water pollution treatment or emission reduction actions.

Table 1. The Chinese Environmental Quality Standards of Surface Water. Unit: mg/L, except pH.

Parameter / Standard Value / Grade	I	II	III	IV	V
pH	6~9				
dissolved oxygen content (DOC) ≥	percentage of oxygen saturation 90% (or 7.5)	6	5	3	2
permanganate index (COD_{Mn}) ≤	2	4	6	10	15
biological oxygen demand (BOD_5, after 5 days of incubation) ≤	3	3	4	6	10
chemical oxygen demand (COD_{Cr}) ≤	15	15	20	30	40
NH_4-N (ammonium nitrogen) ≤	0.15	0.5	1.0	1.5	2.0
oils ≤	0.05	0.05	0.05	0.5	1.0
total nitrogen (TN) ≤	0.2	0.5	1.0	1.5	2.0
total phosphorus (TP) ≤	0.01	0.025	0.05	0.1	0.2
phenolics ≤	0.002	0.002	0.005	0.01	1

Table 1. *Cont.*

Standard Value / Grade / Parameter	I	II	III	IV	V
mercury (Hg) ≤	0.00005	0.00005	0.0001	0.001	0.001
lead (Pb) ≤	0.01	0.01	0.05	0.05	0.1
copper (Cu) ≤	0.01	1.0	1.0	1.0	1.0
zinc (Zn) ≤	0.05	1.0	1.0	2.0	2.0
fluoride (F) ≤	1.0	1.0	1.0	1.5	1.5
selenium (Se) ≤	0.01	0.01	0.01	0.02	0.02
arsenic (As) ≤	0.05	0.05	0.05	0.1	0.1
cadmium (Cd) ≤	0.001	0.005	0.005	0.005	0.01
chromium (Cr^{6+}) ≤	0.01	0.05	0.05	0.05	0.1
cyanide (CN) ≤	0.005	0.05	0.2	0.2	0.2
anionic surfactants ≤	0.2	0.2	0.2	0.3	0.3
Sulfides ≤	0.05	0.1	0.2	0.5	1.0

Table 2. The environmental function and protecting objectives for Chinese surface water classification.

Grade	The Environmental Function and Protecting Objectives for Surface Water
I	Water source, National Nature Reserve
II	Residential drinking water of the first reserve, rare aquatic products habitat, spawning ground for aquatic products and feeding ground
III	Residential drinking water, surface water of the secondary reserve, wintering grounds for aquatic products, migration routes, aquiculture areas and some swimming areas
IV	Industrial water and water for recreation
V	Agricultural water and water for other landscape areas

2.2.2. Interactions between Water Quality and Socioeconomic Development

To analyze the interactions between water quality and socioeconomic development, the relationship between WPI and the gross domestic product (GDP) in the region surrounding the water body was graphed, using version 20.0 of the SPSS software (http://www-01.ibm.com/software/analytics/spss/) to calculate Pearson's correlation coefficient (r). In this analysis, Taihu Lake was divided into three parts (the Shanghai, Zhejiang and Jiangsu sections), because it crosses three regions that have large differences in the level of economic development, and the data of the 110 investigated monitoring sections showed significant differences in the situation of water pollution of the three regions.

3. Results

3.1. Temporal and Spatial Distributions of WPI and Trends from 2005 to 2010

Figures 2–5 present the estimated values of WPI for the 28 large lakes and reservoirs from 2005 to 2010. The water quality in Dalai Lake (Figure 2), Xihu Lake (Figure 3), the Dahuofang Reservoir

(Figure 4) and Taihu Lake in Zhejiang Province (Figure 5) improved greatly between 2005 and either 2006 or 2007 and then remained relatively stable. Although the water quality in Chaohu and Dianchi lakes deteriorated from 2007 to 2009 and then improved in 2010 (Figure 5), the overall water quality of these lakes remained mostly stable during the study period. Due to the Hg concentration at two monitoring sections (0.006853 and 0.004352 mg/L respectively) in 2005, Dalai Lake greatly exceeded the Grade III threshold value (0.0001 mg/L), increasing the WPI to 76.99 in 2005 (Figure 2); from 2006 to 2010, the Hg content was below this threshold value. Other pollution factors did not change significantly during this period, so the overall water quality in Dalai Lake did not change substantially. Water monitoring in Xihu Lake showed that the As content exceeded the Grade III standard in 2005. At the Huxin and Shaoniangong monitoring sections, As contents were 0.91 and 1.84 mg/L, respectively, which are equivalent to 9.1- and 18.4-times the Grade IV threshold value (0.10 mg/L), resulting in a high WPI in 2005, while the water quality started to improve in 2006. The water quality in Dahuofang Reservoir deteriorated in 2005 and 2007 (Figure 4) because of the high Hg concentration (0.005 and 0.00168 mg/L in 2005 and 2007, respectively, which was 100- and 33.6-times the Grade II standard (0.00005 mg/L)). This led to a much higher WPI than in the other reservoirs. However, the water quality was stable in the other years.

Taihu Lake was the most seriously polluted water body. With this exception, the water quality in the municipal lakes and large reservoirs was generally better than that in the large freshwater lakes. Figure 6 presents the mean value of WPI for northern and southern lakes from 2005 to 2010, which indicates that WPI was generally higher for northern lakes (12.71 ± 4.14) than for southern lakes (9.97 ± 1.28). Although previous studies [33,36,37] showed that the changes in water quality are not only influenced by human activities, but also by natural drivers (especially lake water level), considering the small changes of water levels from 2005 to 2010, this work only considered the influence from human activities.

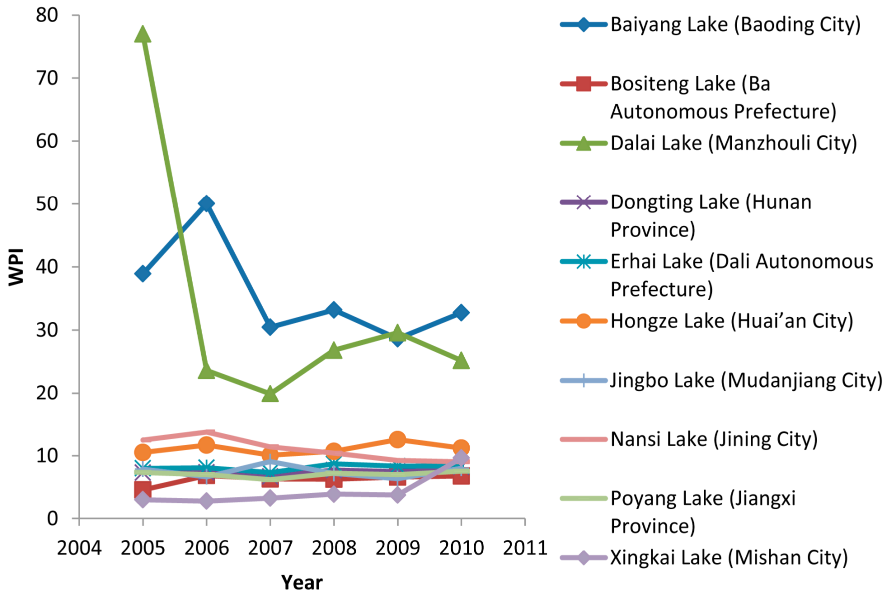

Figure 2. Changes in water pollution index (WPI) for China's key freshwater lakes from 2005 to 2010.

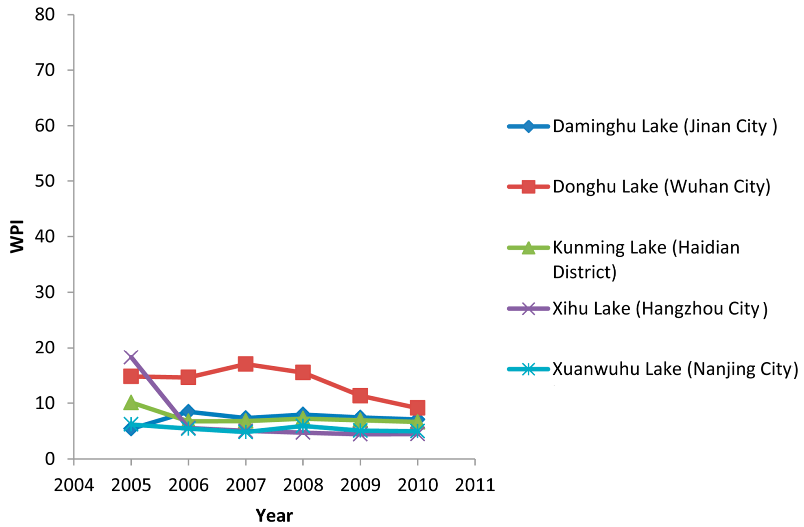

Figure 3. Changes in WPI for China's key municipal lakes from 2005 to 2010.

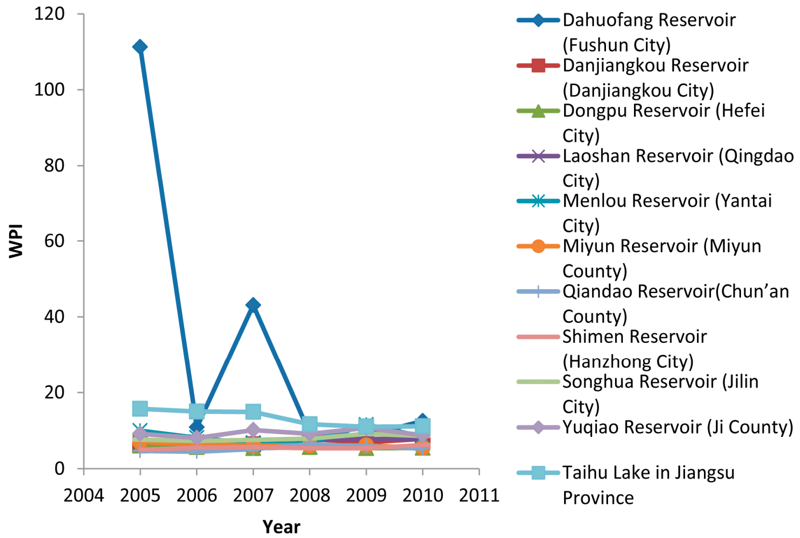

Figure 4. Changes in WPI for China's key reservoirs from 2005 to 2010.

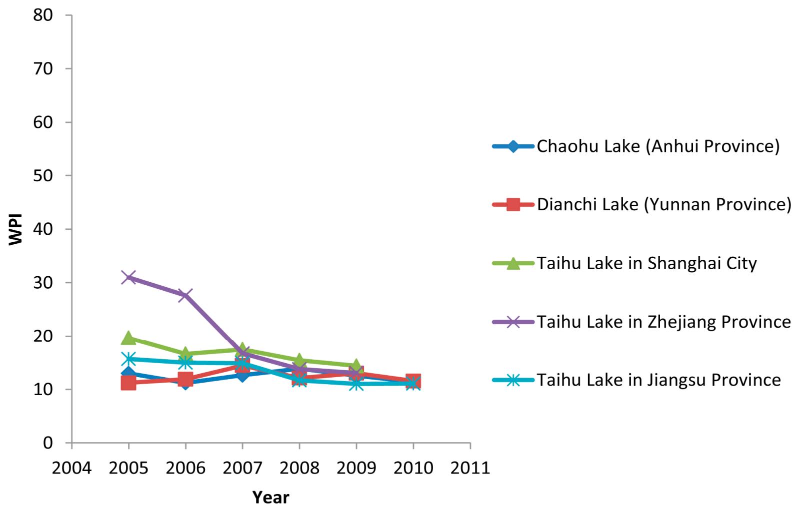

Figure 5. Changes in WPI for Taihu Lake, Chaohu Lake and Dianchi Lake from 2005 to 2010.

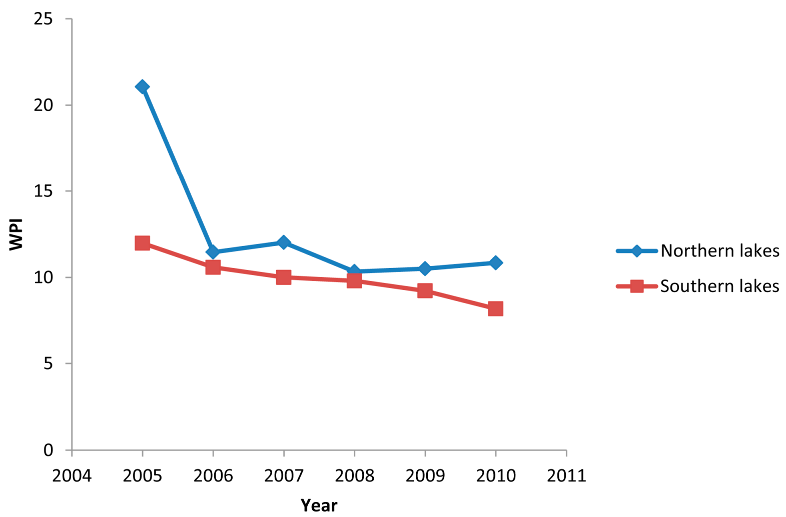

Figure 6. Mean WPI for northern and southern lakes from 2005 to 2010.

3.2. Analysis of the Pollutant Weights for the Key Lakes and Reservoirs

To understand the key pollutants in the investigated lakes and reservoirs and to analyze their changes during the study period, the K-Shares were calculated for each pollutant from 2005 and 2010. Tables A2–A5 summarize the K-Shares for the three major pollution factors in each water body.

Table A2 shows that the three main pollution factors changed in Dongting, Poyang and Erhai lakes between 2005 and 2010. The main pollution factors in Dongting Lake changed from TN, TP and Pb to fluoride, DOC and oils, especially as a result of contamination by the large number of chemical factories located in the Dongting Lake basin [32]. The main pollution factors in Poyang Lake changed from TN, TP and oils to DOC, fluoride and phenolics, showing a change in the specific pollutants released by the nearby chemical factories [38]. The main pollution factors in Erhai Lake changed from TN, TP and Pb to phenolics, F and COD_{Cr}, largely due to the increasing pollution by the synthetic fiber, papermaking and chemical industries. In the remaining lakes, at least one of the three main factors did not change during the investigated period.

Tables A3 and A4 show that the three main pollution factors slightly changed in the municipality lakes and reservoirs between 2005 and 2010. No changes were detected in Kunming Lake, the Laoshan Reservoir, the Menlou Reservoir and Songhua Reservoir, which were mostly dominated by TN, TP and COD, highlighting a major contribution from organic pollutants. However, the K-share of these three factors significantly changed between 2005 and 2010: for example, in the Kunming Lake, the K-share of TN increased from 16.60% to 20.77%, the K-share of COD_{Cr} decreased from 14.32% to 11.20% and the K-share of TP decreased from 13.43% to 10.53%. Due to the decrease of COD_{Mn}, BOD_5 and NH_4-N, the share ratio of TN increased, although the monitoring value and WPI of TN both decreased between 2005 and 2010.

Table A5 shows that TP was an important pollution factor in the Chaohu Lake basin during the investigated period, while oils became more important in 2010 and the form of nitrogen changed from NH_4-N to TN. This reflects the influences of agricultural nonpoint source pollution, wastewater from the livestock breeding industry and the increasing importance attributed to industrial pollutants. Among the three primary pollutants for Dianchi Lake, TN was important during all of the investigated period; but,

NH_4-N was replaced by TP as the most important pollutant, moving from 2005 to 2010, and COD_{Mn} became relevant in 2010. This suggests that Dianchi Lake was mainly affected by organic pollutants. For Taihu Lake, TP was a relevant pollutant in both 2005 and 2010, but decreased in importance during this period, whereas oils and Se in 2005 were replaced by TN and COD_{Cr} in 2010. In this lake, four to six sections had pollution factor levels that were 15- to 40-times the corresponding standard value.

4. Discussion

4.1. Correlation between WPI and Regional GDP

There are some studies that have statistically examined the impacts of regional economic growth on water quality. Ren *et al.* [39] investigated the relationship between water quality and urbanization in Shanghai, and the results revealed that rapid urbanization corresponded with rapid degradation of water quality. Yin *et al.* [40] found that strong associations between land use, population density and water quality resulted from the contribution of untreated domestic wastewater and non-point pollution sources to waterways in Shanghai. We used a similar analysis method, by observing the correlation between WPI and GDP, to measure the impact of regional economic development on water quality in relevant watersheds of China. Figure 7 compares WPI with regional GDP from 2005 to 2010 for the regions where the 28 major lakes and reservoirs are located. Table 3 and Table A6 list these water bodies and, in brackets, the region whose GDP was used in this analysis. For example, Chaohu, Dianchi, Dongting and Poyang are large lakes, and their basins cover most of the area of their respective provinces; thus, the economy of the whole basin plays an important role in these provinces. Accordingly, the GDP of the entire province was used for the analysis of these lakes. While for the smaller water bodies and the municipal lakes, the total GDP of the city or cities sharing the water body was considered. Due to the fact that Taihu Lake crosses the boundaries of three provinces or cities, the economies of these three regions have an important impact on water quality in the lake. Therefore, the GDP value for Taihu Lake in Figure 7 is based on the corresponding provincial or city GDP values (as is shown in Table A7).

The impact of regional economic development on water quality can be measured based on the correlation between WPI and GDP. Table 3 shows significantly positive correlations for Xingkai Lake (0.827), the Danjiangkou Reservoir (0.817) and Songhua Reservoir (0.826). The reason for this change was that the basins were undergoing accelerated industrialization and urbanization during the study period, and a large number of industrial factories failed to perform adequate (or any) treatment of their sewage discharge. In addition, there were many rural non-point sources of pollution, largely due to agricultural activities. The result was that watershed water quality deteriorated and eutrophication increased during the study period. For example, the water quality in Xingkai Lake was Grade II from 2005 to 2007, and none of the indicators exceeded the limits for this grade. However, beginning in 2008, water quality of Grade III began to appear, with COD_{Mn} exceeding the value for Grade II, indicating an increasing level of organic pollution.

In 2005, the TN content in the Danjiangkou Reservoir was 1.98-times the limit for Grade II, accounting for about 35% of the total pollution; in 2006, the TN content increased to 2.2-times the limit for Grade II, accounting for more than 25% of the total pollution, and the water quality declined to Grade IV. In 2006, the Yangtze River Water Resources Protection Bureau surveyed pollution sources in the region surrounding the Danjiangkou Reservoir, finding 124 significant sources in the upstream regions of the Yangtze River that flowed into the reservoir. Most of the towns and industrial enterprises surrounding the reservoir were small sized and had a relatively backward infrastructure. Sewage was discharged without treatment by small chemical industries, such as printing and dyeing factories, and the surrounding urban residents also contributed to the domestic sewage discharge into the Danjiangkou Reservoir.

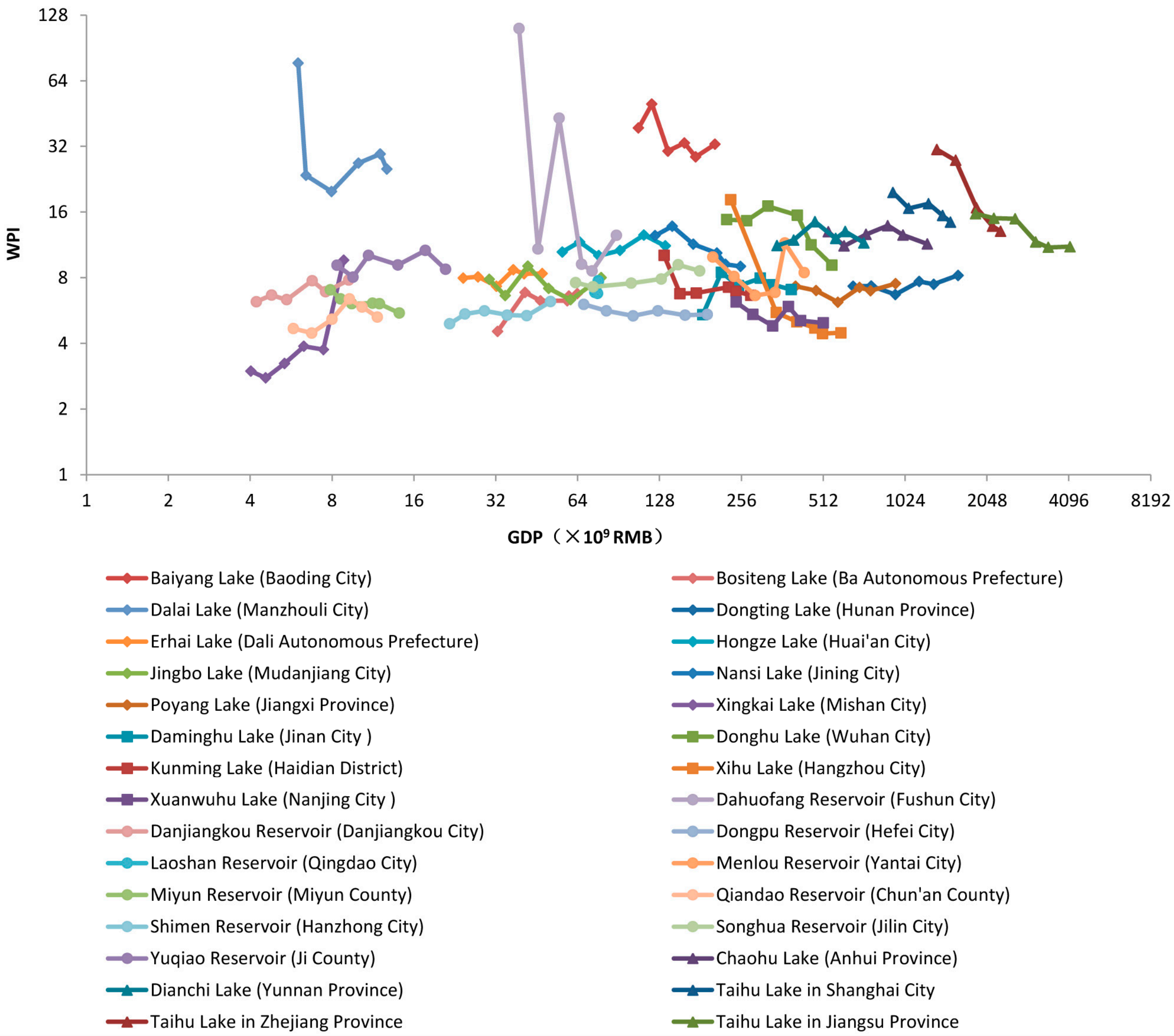

Figure 7. Relationship between WPI and GDP for the investigated 28 key lakes and reservoirs from 2005 to 2010.

In Songhua Reservoir, the main pollutants were TN and TP, and the TN level was 1.7-times the standard value for Grade III quality, accounting for about 20% of the total pollution and causing the water quality to deteriorate to Grade IV or V. The water pollution mainly originated from urban sewage and industrial pollution in the upper reaches of the tributaries of the reservoir, pollution caused by tourism activities around the lake and non-point source agricultural pollution. Due to the lack of an overall comprehensive development policy or environmental governance, pollutant emissions increased, aggravating water pollution.

Table 3. Correlations (Pearson's *r*) between WPI and GDP of the 28 key lakes and reservoirs. The region whose GDP was used in this analysis is provided in brackets. Values labeled with an * were statistically significant ($p < 0.05$, two-tailed test).

	Lake or Reservoir		*r*	*p* (Two-Tailed)
Key freshwater lakes	Baiyang Lake (Baoding City)		−0.601	0.207
	Bositeng Lake (Ba Autonomous Prefecture)		0.670	0.146
	Dalai Lake (Manzhouli City)		−0.459	0.360
	Dongting Lake (Hunan Province)		0.703	0.119
	Erhai Lake (Dali Autonomous Prefecture)		0.476	0.340
	Hongze Lake (Huai'an City)		0.418	0.409
	Jingbo Lake (Mudanjiang City)		−0.043	0.936
	Nansi Lake (Jining City)		−0.928 *	0.008
	Poyang Lake (Jiangxi Province)		0.311	0.548
	Xingkai Lake (Mishan City)		0.827 *	0.042
Key municipal lakes	Daminghu Lake (Jinan City)		0.246	0.638
	Donghu Lake (Wuhan City)		−0.766	0.075
	Kunming Lake (Haidian District)		−0.580	0.228
	Xihu Lake (Hangzhou City)		−0.788	0.063
	Xuanwuhu Lake (Nanjing City)		−0.569	0.239
Key reservoirs	Dahuofang Reservoir (Fushun City)		−0.645	0.166
	Danjiangkou Reservoir (Danjiangkou City)		0.817 *	0.047
	Dongpu Reservoir (Hefei City)		−0.666	0.149
	Laoshan Reservoir (Qingdao City)		0.756	0.082
	Menlou Reservoir (Yantai City)		0.041	0.939
	Miyun Reservoir (Miyun County)		−0.886 *	0.019
	Qiandao Reservoir (Chun'an County)		0.624	0.186
	Shimen Reservoir (Hanzhong City)		0.757	0.081
	Songhua Reservoir (Jilin City)		0.826 *	0.043
	Yuqiao Reservoir (Ji County)		0.221	0.674
China's "three lakes"	Chaohu Lake (Anhui Province)		−0.171	0.746
	Dianchi Lake (Yunnan Province)		0.063	0.906
	Taihu Lake	Shanghai City	−0.897 *	0.039
		Zhejiang Province	−0.970 *	0.006
		Jiangsu Province	−0.921 *	0.009

In contrast, significantly negative correlations were observed for Taihu Lake in Zhejiang Province (−0.970), Taihu Lake in Jiangsu Province (−0.921) and Nansi Lake (−0.928). The main pollution factors for Taihu Lake in Zhejiang Province were NH_4-N and TP. Among the monitoring sections, 37.1% had water quality worse than Grade V. Since 2008, the water quality of Taihu Lake in Zhejiang Province has improved significantly, and the number of sections with water quality worse than Grade V decreased to 33.7% in 2007, 24.7% in 2008 and 19.1% in 2009. The major pollution factors for Taihu Lake in Jiangsu Province were TN and TP, and 66.7% of the monitoring sections were worse than Grade V in 2005, the remaining ones being in Grade V. The situation has improved since 2007, when monitoring sections with Grade IV appeared, and WPI started to decrease significantly in 2008. As the economies of the provinces surrounding Taihu Lake achieved rapid, but more stable growth, water pollution decreased continuously. This is mainly due to the implementation of comprehensive pollution control measures, including the closure of some papermaking, chemical, printing and dyeing factories, adjustment of the regional industrial structure and construction of sewage treatment facilities. Thus, the regions around Taihu Lake may have entered a stage in which the environmental quality will continue to improve despite ongoing socioeconomic development.

Nansi Lake's main pollutant was TP (at up to two-times the limit for Grade III), which accounted for 20% of the total pollution. TN and oils each accounted for about 15% of the total pollution. In 2005, the lake's water quality was Grade V, and it degraded to worse than V in 2006, but from 2007 onwards, it gradually improved to Grade IV. In 2006, under the China's south-to-north water diversion project, Shandong Province implemented pollution emission standards, with COD_{Cr} limited to 1/6 the value in the national standard, and NH_4-N limited to 1/7 the national value. All land within 15 km from the coast became the key component of the protection of the Nansi Lake drainage area. Since the implementation of its "11th Five-Year Plan", Weishan County, where Nansi Lake is located, has closed 38 enterprises that could not meet the new emission standards. Thus, the improvements in Nansi Lake have resulted from stricter pollution control standards and adjustment of the industrial structure.

Similar negative correlations were found for Taihu Lake in Shanghai City (−0.897) and the Miyun Reservoir (−0.886). The main reason is that the governments of the surrounding regions developed new regulations and implemented regional water pollution control projects. The water quality of Taihu Lake in Shanghai City was worse than Grade V from 2005 to 2009, but WPI decreased from 19.67 in 2005 to 14.40 in 2009; and the main pollution factors were NH_4-N, BOD_5 and oils, mostly produced by the chemical factories in Shanghai. However, since the comprehensive management of water pollution was implemented for the Taihu River Basin in 2008, there has been some initial improvement of water quality. All pollutant indices for the Miyun Reservoir were close to the limit for Grade II, and NH_4-N accounted for about 16% of total pollution. Miyun County invested 29.5×10^6 RMB over three years to protect the Miyun Reservoir, starting in 2005. This effort focused on recycling wastes from the surrounding livestock and aquaculture industries and maintained the water quality at Grades II or III.

Table 3 shows other water bodies with a strong negative correlation between WPI and GDP, although the correlation was not significant. For example, the water quality in Dongpu Reservoir (Hefei City) improved despite economic development ($r = -0.666$), largely as a result of a small, but comprehensive watershed treatment project conducted in Hefei City in 2009. Similarly, the Dahuofang Reservoir (Fushun City) showed improved water quality despite economic development ($r = -0.645$); in 2005, its WPI (111.25) was higher than that of any other reservoir, but in 2006, it had decreased to 10.84. From 2006 to 2010, WPI fluctuated, but remained near that level. The significant improvement of its water quality resulted from a special environmental protection action plan that controlled the activities of industrial, mining and farming enterprises in the protection zone around the reservoir, which effectively reduced the pollution load reaching the reservoir.

In general, the correlation between WPI and GDP is not significant in the majority of water bodies. In the investigated period, most governmental authorities had identified the environmental pressures brought by the industrialization and urbanization development. Consequently, the governments started to implement several pollution control measures to reduce the negative effects as a result of the economic development. Finding out the correlation between WPI and regional GDP could support the identification of the key lakes and reservoirs (characterized by a positive correlation between WPI and

GDP), where more strict control measures are required for implementation. On the other hand, lakes and reservoirs, which show a negative correlation between WPI and GDP, provide evidence of the excellent management plans, which set good examples for other case studies. This provides a positive and negative reference for the governmental authorities to coordinate regional economic development and water ecological system protection.

4.2. Types of Relationships between WPI and GDP

We defined four categories of relationships between WPI and GDP based on their median values of all data obtained from the 28 water bodies at the six time points (each year from 2005 to 2010): low or high WPI combined with low or high GDP (Figure 8). The low/low and high/high combinations accounted for 33.3% and 30.0% of the total water bodies, respectively; while, the combination of low WPI with high GDP accounted for 20.0% of the relationships, *versus* 16.7% for high WPI with low GDP.

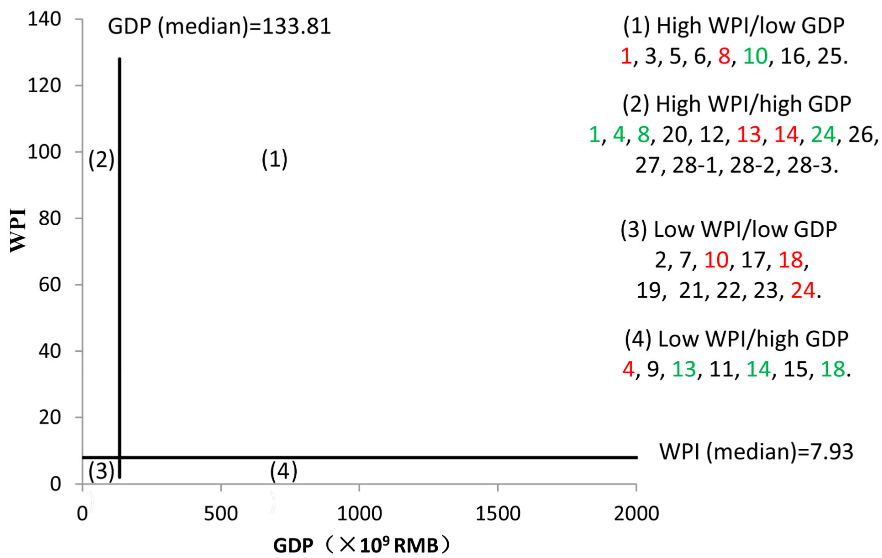

Figure 8. The division of the 28 water bodies into four categories, based on the median WPI and GDP. 1. Baiyang Lake (Baoding City); 2. Bositeng Lake (Ba Autonomous Prefecture); 3. Dalai Lake (Manzhouli City); 4. Dongting Lake (Hunan Province); 5. Erhai Lake (Dali Autonomous Prefecture); 6. Hongze Lake (Huai'an City); 7. Jingbo Lake (Mudanjiang City); 8. Nansi Lake (Jining City); 9. Poyang Lake (Jiangxi Province); 10. Xingkai Lake (Mishan City); 11. Daminghu Lake (Jinan City); 12. Donghu Lake (Wuhan City); 13. Kunming Lake (Haidian District); 14. Xihu Lake (Hangzhou City); 15. Xuanwuhu Lake (Nanjing City); 16. Dahuofang Reservoir (Fushun City); 17. Danjiangkou Reservoir (Danjiangkou City); 18. Dongpu Reservoir (Hefei City); 19. Laoshan Reservoir (Qingdao City); 20. Menlou Reservoir (Yantai City); 21. Miyun Reservoir (Miyun County); 22. Qiandao Reservoir (Chun'an County); 23. Shimen Reservoir (Hanzhong City); 24. Songhua Reservoir (Jilin City); 25. Yuqiao Reservoir (Ji County); 26. Chaohu Lake (Anhui Province); 27. Dianchi Lake (Yunnan Province); 28-1. Taihu Lake in Shanghai City; 28-2. Taihu Lake in Zhejiang Province; 28-3. Taihu Lake in Jiangsu Province. For some water bodies that appear in two categories from 2005 to 2010, red represents the initial state (in 2005) and green represents the final state (in 2010).

Water bodies with low WPI and low GDP were located on China's east coast (40.0%), in the central inland area (40.0%) and the western regions (20%) and were mainly reservoirs (70%). These regions had relatively small economies and, thus, a relatively low level of water pollution. However, the strategic goal of developing ecological tourism in some areas effectively improved the water quality: for example, Chun'an County established the first environmental special protection fund to protect Qiandao Reservoir. Similarly, Bositeng Lake and Jingbo Lake took advantage of their natural resources to develop ecological tourism. However, the fragile ecological environment of these regions means that their governments must continue to take measures to prevent damage to these resources (including water pollution) in the future.

Water bodies with high WPI and high GDP were mainly located on China's east coast (69.2%), and a few of them in the central inland (15.4%) and the western regions (15.4%). These basins were inside or near densely populated areas and economic centers and were surrounded by numerous polluting industries. For example, the chemical industry was the main pollution source in the Taihu Lake basin, whereas the chemical fertilizer and pesticide industries were the dominant pollution sources in Nansi Lake. The pollution level in Taihu, Chaohu and Dianchi lakes was sufficiently serious that they have been listed by the government as key project areas for water pollution prevention.

Water bodies with low WPI and high GDP were located mainly in east China (71.4%) and central China (28.6%), and they were mainly urban lakes located in the middle and lower reaches of the Yangtze River. The combination of the surrounding urban development conditions, based on industries with a relatively low pollution level (such as tourism and new high technology industries), with the implementation of effective measures to control point source pollution and reduce total pollution has improved the water quality in these areas. For example, in Xuanwuhu Lake, an artificial ecosystem was built to perform ecological restoration, and in Daminghu Lake, a comprehensive program of sewage removal, relocation of polluting industries, dredging and ecological restoration was implemented. These measures protected both economic development and water quality.

Bodies of water with high WPI and low GDP were also located in east China (50%) and the central inland are (50%). Agriculture and animal husbandry were the main industries in the surrounding areas, where extensive (rather than intensive) management led to high pollution emissions combined with low economic benefits. Poor regulations and measures to protect the water environment led to a low treatment rate for sewage, causing eutrophication when the pollution exceeded the water's self-purification capacity. The main pollution sources for Dalai Lake came from animal husbandry, for the Dahuofang Reservoir the manufacturing and livestock breeding industries and for the Yuqiao Reservoir soil erosion and leaching from waste dumps upstream of the reservoir. In addition, all of these water bodies were characterized by high pressure from nonpoint pollution sources and a low treatment rate of domestic sewage.

Some patterns of change over time were negative trends. In some cases, WPI increased with little change in GDP: for example, Xingkai Lake (Mishan City) changed from low WPI with low GDP to high WPI with low GDP and Dongting Lake (Hunan Province) changed from low WPI with high GDP to high WPI with high GDP. Both trends revealed that the damage to the water environment caused by GDP growth in these areas was relatively high and increasing. The second trend concerns the concomitant increase in GDP and WPI: for example, Songhua Reservoir (Jilin City) changed from low to high WPI and GDP values, which showed that economic development led to increased deterioration of the water environment.

There were also some positive trends. In some cases, WPI decreased with little change in GDP, as in the case of Kunming Lake (Haidian District) and Xihu Lake (Hangzhou City), where WPI changed from high to low, maintaining high GDP. This reflected a regional development strategy that emphasized sustainability and environmentally friendly development. The second positive trend concerns an increase of GDP without a change in WPI, as in the case of Baiyang Lake (Baoding City), Nansi Lake (Jining City) and the Dongpu Reservoir (Hefei City). This resulted from the local policy that strictly limited the possible negative effects brought by human activities.

5. Conclusions

In this paper, the water quality in 28 of China's key water bodies and its relationship with socioeconomic development from 2005 to 2010 were analyzed. Overall, the proposed comprehensive water pollution index (WPI) values for municipal lakes and for Taihu Lake decreased, indicating decreasing levels of pollution. However, the water quality of the freshwater lakes and the large reservoirs did not change significantly. Pollution levels tended to be higher in the northern regions and lower in the southern ones, mainly due to differences in the rate of socioeconomic development, in population and industrial density and in the influence of natural conditions (e.g., the much lower precipitation in the northern areas). Water quality in Taihu Lake basin, which is located in China's most economically developed area, has gradually improved despite the region's rapid economic growth, but the water quality of other areas showed little change and had little relationship with socioeconomic development.

The fact that most of the water bodies were characterized by a water quality of Grade V or worse in 2005 and 2010 highlights the considerable need for improvement. The three primary pollutants of most water bodies did not change significantly during the study period and were dominated by organic pollutants; but the main pollution factors for Dongting, Poyang and Erhai lakes changed greatly, probably due to changes in the industrial structure around the lakes. Overall, China's economic development since 2005 has not been accompanied by equally rapid deterioration of the water quality of major lakes and reservoirs, and measures to prevent or mitigate water pollution in the Taihu Lake basin are beginning to prove effective. However, although water quality did not show a deterioration trend in time, it also did not improve greatly in most areas, suggesting that considerable additional work must be done. In addition, some of the pollution weights increased gradually due to the widespread presence of chemical, metallurgical, mining and other industries in the areas surrounding the water body. Based on the results of our study, the governmental authorities responsible for each water body should provide more efforts to rationalize the regional industrial structure and to control pollution by accounting for the characteristics of the natural environment surrounding the water bodies.

The analysis of the correlation between WPI and GDP showed relatively few significant relationships, although we found significant positive correlations for 10% of the water bodies *versus* significant negative correlations for 16.7% of them, and no significant correlation for the remaining ones (73.3%). Moreover, the combination of low WPI with low GDP and high WPI with high GDP were the dominant combinations, accounting for 33.3% and 30.0% of the water bodies, respectively.

The present work focused on the temporal and spatial distribution of lake and reservoir water quality in China and changes in its relationship with GDP. The main aim was to find out the relationship between the trend in water quality, the main pollution factor and regional economic development. The obtained results can provide guidance for decision makers to perform effective management strategies for water pollution control, such as selecting the key pollutant and key lakes where pollution control and the implementation of economic development policies are required.

It should be noted that a large amount of information is merged when applying the WPI approach, and some useful information may be ignored when using WPI assessment. For example, WPI cannot reflect the change in the temporal trend of a single pollution factor (WPI may stay steady when some pollution factors improve or some pollution factors deteriorate); or WPI may rise when a few pollution factors get worse. Therefore, further research on the temporal and spatial distribution of eutrophication and heavy metal pollution in the investigated water bodies is strongly recommended. Moreover, water quality could be affected by many factors interacting in several complex ways, and socioeconomic development cannot be the only important factor; in addition, GDP provides a simpler and less accurate approach to evaluate economic development than using a more detailed analysis of the actual socio-economic structure of a region. Accordingly, the inclusion of additional factors, such as population, policy and regulations, and natural conditions that can affect water quality is strongly recommended in the future development of this work. Finally, it is important to specify that the present analysis did not include all of the Chinese rivers or the many smaller water bodies that are also important to local communities and did not include data for most of the northern and western regions of China. Thus, future research activities should investigate water quality in these water bodies and areas.

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Author Contributions

The paper was inspired by the collaboration among Yan Zhang, Xiaojie Meng and Jinyan Zhan. They designed the research together. Xiangyi Yu, Yingying Chai, Yating Li and Jinjian Li contributed much to the data processing. Andrea Critto did the reviewing work. The most writing work was done by Xiaojie Meng, but all of the other authors participated in reviewing the manuscript and discussing the results. All authors read and approved the final manuscript.

Appendix

Table A1. The data of Xuanwuhu Lake (Nanjing City, Jiangsu Province, two sections) from 2005 to 2010. Unit: mg/L, except special notes and pH.

	2005			2006			2007			2008			2009			2010			Standard
	Section 1	Section 2	K	Section 1	Section 2	K	Section 1	Section 2	K	Section 1	Section 2	K	Section 1	Section 2	K	Section 1	Section 2	K	Value
Water temperature (°C)	18.2	17.9	-	18.3	17.7	-	18.4	18.4	-	18.1	18.2	-	17.4	17.2	-	19.9	19.8	-	-
Water level (m)	-	-	-	-	-	-	-	-	-	1.49	1.53	-	1.67	1.4	-	1.92	1.36	-	-
pH	8.15	8.16	9.34	8.47	8.24	12.47	8.18	8.17	12.22	8.03	7.97	8.47	8.33	8.28	12.83	8.5	8.47	14.95	6~9
DOC	8.85	8.35	2.08	10.98	9.68	2.58	8.14	8.27	3.78	9.48	9.5	0.22	9.7	9.92	0.72	10.39	10.21	3.98	3
COD_{Mn}	3.64	4.2	6.34	2.77	2.71	5.04	2.84	3.07	6.15	3.51	3.66	6.07	3.27	3.6	6.75	3	3.25	6.29	10
BOD_5	3.16	2.96	8.25	2.01	2.29	6.59	2.17	2.35	7.84	4.13	3.8	11.20	1.93	2.15	6.68	3.52	3.99	12.60	6
NH_4-N	0.244	0.163	2.19	0.193	0.211	2.48	0.255	0.268	3.63	0.428	0.408	4.72	0.288	0.359	4.24	0.122	0.185	2.06	1.5
Oils	0.114	0.104	3.53	0.044	0.058	1.88	0.02	0.02	0.83	0.027	0.032	1.00	0.051	0.056	2.10	0.028	0.027	1.11	0.5
TN	1.85	1.795	19.65	2.469	1.902	26.82	2.217	1.852	28.21	2.571	2.315	27.59	1.987	1.863	25.23	2	1.782	25.38	1.5
TP	0.136	0.172	24.90	0.112	0.112	20.61	0.073	0.074	15.29	0.123	0.114	20.08	0.097	0.114	20.74	0.058	0.083	14.19	0.1
Phenolics	0.0013	0.001	1.86	0.001	0.001	1.84	0.001	0.001	2.08	0.001	0.001	1.69	0.001	0.001	1.97	0.001	0.001	2.01	0.01
Hg	0.00002	0.00002	0.32	0	0	0	0.00003	0.00003	0.52	0.00002	0.00002	0.30	0.00002	0.00002	0.39	0.00002	0.00002	0.40	0.001
Pb	0.005	0.005	1.62	0.005	0.005	1.84	0.005	0.005	2.08	0.00267	0.00267	0.90	0.00096	0.00096	0.38	0.00108	0.00108	0.44	0.05
COD_{Cr}	17.63	17.25	9.40	12	14.75	8.21	12.79	12.71	8.84	13.08	14.17	7.69	8.96	10.92	6.51	7.83	9.83	5.93	30
Cu	0.015	0.015	0.24	0.0112	0.0112	0.21	0.015	0.015	0.31	0.0171	0.0171	0.29	0.02	0.02	0.39	0.02	0.02	0.40	1
Zn	0.01	0.01	0.08	0.008	0.008	0.07	0.025	0.025	0.26	0.016	0.016	0.14	0.01	0.01	0.10	0.01	0.01	0.10	2
F	0.229	0.236	2.51	0.273	0.284	3.42	0.19	0.192	2.65	0.292	0.287	3.27	0.267	0.275	3.55	0.298	0.308	4.07	1.5
Se	0.0006	0.000575	0.48	0.0007	0.000737	0.66	0.000125	0.000125	0.13	0.000244	0.000252	0.21	0.000212	0.000237	0.22	0.000233	0.0002	0.22	0.02
As	0.00838	0.00838	1.35	0.00509	0.00492	0.92	0.00003	0.00003	0.01	0.00118	0.00093	0.18	0.00285	0.00284	0.56	0.0025	0.00182	0.43	0.1
Cd	0.00063	0.000625	2.02	0.0005	0.0005	1.84	0.0005	0.0005	2.08	0.0005	0.0005	1.69	0.0005	0.0005	1.97	0.0005	0.0005	2.01	0.005
Cr^{6+}	0.002	0.002	0.65	0.002	0.002	0.74	0.002	0.002	0.83	0.002	0.002	0.68	0.002	0.002	0.79	0.002	0.002	0.81	0.05
Cyanide	0.002	0.002	0.16	0.002	0.002	0.18	0.001	0.001	0.10	0.0016	0.0016	0.14	0.002	0.002	0.20	0.002	0.002	0.20	0.2
LAS	0.06	0.05	2.96	0.03	0.002	1.53	0.03	0.03	2.08	0.06	0.06	3.39	0.05	0.06	3.60	0.04	0.03	2.35	0.3
S	0.002	0.002	0.06	0.02	0.002	0.07	0.002	0.002	0.08	0.002	0.002	0.07	0.002	0.002	0.08	0.002	0.002	0.08	0.5
WPI	6.038	6.328	-	5.718	5.149	-	4.907	4.708	-	6.051	5.754	-	4.926	5.247	-	4.852	5.083	-	-

Note: "Section 1" denotes northwest monitoring section; "Section 2" denotes southeast monitoring section; "TN" denotes total nitrogen; "TP" denotes total phosphorus; "LAS" denotes linear alklybezene sulfonates; "WPI" denotes water pollution index.

Table A2. The weights for the three major pollution factors for China's key freshwater lakes at the start (2005) and end (2010) of the investigated period. The major pollution factors listed that were the top three in both 2005 and 2010 for a given water body are highlighted in grey.

Lake or Reservoir	Year	Weights for the Three Major Pollution Factors (%)			Lake or Reservoir	Year	Weights for the Three Major Pollution Factors (%)		
Baiyang Lake	2005	F	TN	TP	Bositeng Lake	2005	COD_{Mn}	TN	pH
		21.53	20.05	15.41			19.69	19.30	17.30
	2010	F	DOC	TN		2010	Phenolics	COD_{Mn}	F
		29.64	25.26	19.43			18.78	13.80	13.53
Dalai Lake	2005	Phenolics	Zn	TP	Dongting Lake	2005	TP	TN	Pb
		72.77	4.67	4.52			33.18	17.08	8.13
	2010	Phenolics	Se	DOC		2010	F	DOC	Oils
		26.22	18.50	17.15			24.96	20.47	7.32
Erhai Lake	2005	TN	TP	Pb	Hongze Lake	2005	TP	TN	BOD_5
		13.50	12.89	11.49			26.62	23.24	6.63
	2010	Phenolics	F	COD_{Cr}		2010	TP	TN	Oils
		13.86	13.25	12.29			24.56	17.79	8.93
Jingbo Lake	2005	TP	COD_{Mn}	TN	Nansi Lake	2005	TP	TN	Oils
		25.61	22.41	10.09			22.26	15.16	15.08
	2010	DOC	F	COD_{Mn}		2010	TP	COD_{Cr}	COD_{Mn}
		23.98	19.43	16.96			31.33	14.06	9.39
Poyang Lake	2005	TP	TN	Oils	Xingkai Lake	2005	COD_{Mn}	BOD_5	pH
		34.31	10.92	7.52			29.53	15.91	14.30
	2010	DOC	F	Phenolics		2010	DOC	F	COD_{Mn}
		32.33	15.74	7.99			28.42	11.23	8.67

Table A3. The weights for the three major pollution factors for China's key municipal lakes at the start (2005) and end (2010) of the investigated period. The major pollution factors listed that were the top three in both 2005 and 2010 for a given water body are highlighted in grey.

Lake or Reservoir	Year	Weights for the Three Major Pollution Factors (%)			Lake or Reservoir	Year	Weights for the Three Major Pollution Factors (%)		
Daminghu Lake	2005	TN	BOD_5	COD_{Cr}	Donghu Lake	2005	TP	TN	Oils
		46.99	11.14	9.85			30.56	14.26	9.11
	2010	TN	pH	Cr		2010	TP	TN	COD_{Cr}
		59.90	8.40	6.64			20.10	15.26	11.99
Kunming Lake	2005	TN	COD_{Cr}	TP	Xihu Lake	2005	As	TN	TP
		16.60	14.32	13.43			71.59	8.16	4.07
	2010	TN	COD_{Cr}	TP		2010	TN	pH	COD_{Cr}
		20.77	11.20	10.53			34.96	13.11	10.30
Xuanwuhu Lake	2005	TP	TN	COD_{Cr}					
		24.90	19.65	9.40					
	2010	TN	pH	TP					
		25.38	14.95	14.19					

Table A4. The weights for the three major pollution factors for China's key reservoirs at the start (2005) and end (2010) of the investigated period. The major pollution factors listed that were the top three in both 2005 and 2010 for a given water body are highlighted in grey.

Lake or Reservoir	Year	Weights for the Three Major Pollution Factors (%)			Lake or Reservoir	Year	Weights for the Three Major Pollution Factors (%)		
Dahuofang Reservoir	2005	Hg	TN	Cd	Danjiangkou Reservoir	2005	TN	pH	COD_{Cr}
		89.88	4.00	1.96			28.57	9.15	8.68
	2010	TN	TP	Mn		2010	TN	Pb	Hg
		42.47	15.47	6.33			26.12	8.24	8.01
Dongpu Reservoir	2005	COD_{Cr}	TN	TP	Laoshan Reservoir	2005	TN	TP	F
		13.74	12.62	12.57			40.27	10.22	7.54
	2010	TN	COD_{Cr}	TP		2010	TN	TP	F
		15.72	14.24	9.58			39.07	10.99	7.49
Menlou Reservoir	2005	TN	pH	COD_{Cr}	Miyun Reservoir	2005	TN	COD_{Mn}	pH
		59.59	7.20	5.04			19.20	10.97	8.24
	2010	TN	pH	COD_{Cr}		2010	TN	COD_{Mn}	TP
		52.87	7.63	7.32			14.27	12.12	10.90
Qiandao Reservoir	2005	TN	Phenolics	TP	Shimen Reservoir	2005	TP	DOC	Phenolics
		37.39	10.68	9.40			14.64	12.95	12.20
	2010	TN	TP	Oils		2010	TP	TN	BOD_5
		34.44	9.59	7.57			13.51	12.81	9.38
Songhua Reservoir	2005	TN	TP	COD_{Mn}	Yuqiao Reservoir	2005	TN	TP	COD_{Cr}
		27.80	26.29	15.76			30.85	12.41	10.70
	2010	TN	TP	COD_{Mn}		2010	TN	TP	COD_{Mn}
		23.92	17.04	9.96			27.69	14.02	10.49

Table A5. The weights for the three major pollution factors for Taihu Lake, Chaohu Lake and Dianchi Lake at the start (2005) and end (2010) of the investigated period. The major pollution factors listed that were the top three in both 2005 and 2010 for a given water body are highlighted in grey.

Lake or Reservoir	Year	Weights for the Three Major Pollution Factors (%)			Lake or Reservoir	Year	Weights for the Three Major Pollution Factors (%)		
Chaohu Lake	2005	TP	TN	NH_4-N	Dianchi Lake	2005	NH_4-N	TP	TN
		20.30	17.30	8.40			23.37	21.99	14.09
	2010	Oils	TP	TN		2010	TP	TN	COD_{Mn}
		17.45	17.35	14.47			28.13	26.66	10.63
Taihu Lake in Shanghai	Taihu Lake	TP	oils	Se					
		20.50	11.57	10.67					
		TN	COD_{Cr}	TP					
		29.42	12.65	11.79					

Table A6. Changes in the comprehensive water pollution index (WPI) for the investigated 28 largest water bodies of China from 2005 to 2010. The data sources are listed in brackets.

Lake or Reservoir		**WPI**					
Category	**Name**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Key freshwater lakes	Baiyang Lake (Baoding City)	38.91	50.03	30.46	33.20	28.63	32.72
	Bositeng Lake (Ba Autonomous Prefecture)	4.53	6.85	6.28	6.27	6.60	6.77
	Dalai Lake (Manzhouli City)	76.99	23.62	19.88	26.81	29.57	25.19
	Dongting Lake (Hunan Province)	7.31	7.33	6.70	7.69	7.47	8.20
	Erhai Lake (Dali Autonomous Prefecture)	7.97	8.07	7.30	8.70	8.35	8.36
	Hongze Lake (Huai'an City)	10.50	11.67	10.09	10.68	12.56	11.20
	Jingbo Lake (Mudanjiang City)	7.86	6.63	9.04	7.16	6.34	8.01
	Nansi Lake (Jining City)	12.49	13.77	11.40	10.39	9.22	9.03
	Poyang Lake (Jiangxi Province)	7.32	6.98	6.17	7.21	6.98	7.52
	Xingkai Lake (Mishan City)	2.98	2.78	3.24	3.88	3.74	9.62
Key municipal lakes	Daminghu Lake (Jinan City)	5.42	8.46	7.35	7.96	7.43	7.07
	Donghu Lake (Wuhan City)	14.79	14.62	17.02	15.50	11.33	9.14
	Kunming Lake (Haidian District)	10.13	6.77	6.80	7.24	6.93	6.65
	Xihu Lake (Hangzhou City)	18.25	5.54	5.03	4.70	4.44	4.47
	Xuanwuhu Lake (Nanjing City)	6.18	5.43	4.81	5.90	5.09	4.97

Table A6. *Cont.*

Lake or Reservoir			WPI					
Category	**Name**		**Category**	**Name**	**Category**	**Name**	**Category**	**Name**
Key reservoirs	Dahuofang Reservoir (Fushun City)		111.25	10.84	43.10	9.22	8.60	12.52
	Danjiangkou Reservoir (Danjiangkou City)		6.21	6.66	6.34	7.76	6.89	7.82
	Dongpu Reservoir (Hefei City)		6.04	5.64	5.35	5.64	5.39	5.43
	Laoshan Reservoir (Qingdao City)		6.85	6.99	6.78	7.53	7.76	7.70
	Menlou Reservoir (Yantai City)		9.96	8.11	6.63	6.85	11.54	8.45
	Miyun Reservoir (Miyun County)		7.04	6.39	6.09	6.12	6.08	5.51
	Qiandao Reservoir (Chun'an County)		4.68	4.46	5.17	6.39	5.88	5.29
	Shimen Reservoir (Hanzhong City)		4.92	5.46	5.64	5.39	5.36	6.22
	Songhua Reservoir (Jilin City)		7.60	7.28	7.55	7.90	9.17	8.60
	Yuqiao Reservoir (Ji County)		9.13	8.06	10.12	9.16	10.67	8.75
China's "three lakes"	Chaohu Lake (Anhui Province)		12.99	11.19	12.65	13.86	12.54	11.43
	Dianchi Lake (Yunnan Province)		11.22	11.91	14.45	12.11	13.02	11.56
	Taihu Lake	Shanghai City	19.67	16.64	17.46	15.43	14.40	
		Zhejiang Province	31.00	27.63	16.73	13.77	13.07	
		Jiangsu Province	15.70	14.99	14.90	11.68	11.03	11.10

Table A7. Changes in the regional gross domestic product (GDP) for the investigated 28 largest water bodies of China from 2005 to 2010. The data sources are listed in brackets.

Lake or Reservoir		**GDP ($\times 10^9$ RMB)**					
Category	**Name**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Key freshwater lakes	Baiyang Lake (Baoding City)	107.21	120.00	137.52	158.09	173.76	205.03
	Bositeng Lake (Ba Autonomous Prefecture)	32.50	41.00	46.80	58.70	59.50	63.80
	Dalai Lake (Manzhouli City)	6.00	6.42	7.96	10.01	12.04	12.73
	Dongting Lake (Hunan Province)	659.61	768.87	943.96	1155.50	1305.97	1603.80
	Erhai Lake (Dali Autonomous Prefecture)	24.30	27.53	32.20	37.17	40.68	47.49
	Hongze Lake (Huai'an City)	56.18	65.11	76.52	91.58	112.18	134.51
	Jingbo Lake (Mudanjiang City)	30.28	34.71	42.05	50.11	60.34	78.10
	Nansi Lake (Jining City)	123.36	142.58	170.63	208.20	223.81	254.28
	Poyang Lake (Jiangxi Province)	405.68	482.05	580.03	697.11	765.52	945.13
	Xingkai Lake (Mishan City)	4.03	4.56	5.35	6.31	7.43	8.83
Key municipal lakes	Daminghu Lake (Jinan City)	184.63	216.15	250.01	300.68	334.09	391.05
	Donghu Lake (Wuhan City)	226.12	267.93	320.95	411.55	462.09	551.58
	Kunming Lake (Haidian District)	133.12	152.30	175.00	229.80	244.69	277.16
	Xihu Lake (Hangzhou City)	234.19	344.15	410.02	478.12	509.87	594.92
	Xuanwuhu Lake (Nanjing City)	245.19	282.28	334.01	381.46	423.03	513.06

Table A7. *Cont.*

Lake or Reservoir			GDP (×10^9 RMB)					
Category	Name		Category	Name	Category	Name	Category	Name
Key reservoirs	Dahuofang Reservoir (Fushun City)		39.02	45.75	54.72	66.24	72.40	89.02
	Danjiangkou Reservoir (Danjiangkou City)		4.22	4.80	5.45	6.76	7.57	9.21
	Dongpu Reservoir (Hefei City)		67.42	81.78	102.44	126.28	159.15	192.05
	Laoshan Reservoir (Qingdao City)		74.09	74.94	75.80	76.16	76.26	76.36
	Menlou Reservoir (Yantai City)		201.25	240.58	288.00	340.92	370.18	435.85
	Miyun Reservoir (Miyun County)		7.89	8.60	9.46	11.27	11.95	14.15
	Qiandao Reservoir (Chun'an County)		5.77	6.74	8.00	9.27	10.33	11.75
	Shimen Reservoir (Hanzhong City)		21.66	24.68	29.12	35.26	41.62	50.97
	Songhua Reservoir (Jilin City)		62.97	72.89	100.80	130.02	150.01	180.06
	Yuqiao Reservoir (Ji County)		8.35	9.55	10.90	13.98	17.63	20.93
China's "three lakes"	Chaohu Lake (Anhui Province)		535.02	611.25	736.09	885.17	1006.28	1235.93
	Dianchi Lake (Yunnan Province)		346.18	398.81	477.25	569.21	616.98	722.42
	Taihu Lake	Shanghai City	924.77	1057.22	1249.40	1406.99	1504.65	1716.60
		Zhejiang Province	1341.77	1571.85	1875.37	2146.27	2299.04	2772.23
		Jiangsu Province	1859.87	2174.21	2601.85	3098.20	3445.73	4142.55

Note: GDP values for each lake and reservoir were obtained (based on data for the specified city or region) from http://www.stats.gov.cn/ [41].

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Wang, S.M.; Dou, H.S. *Chinese Lakes*; Science Press: Beijing, China, 1998.
2. Qin, B.Q.; Hu, W.P.; Chen, W.M. *Water Environment Evolution Process and Mechanism of Taihu Lake*; Science Press: Beijing, China, 2004.

3. Shang, Z.T.; Ren, J.; Qin, M.R.; Xia, Y.; He, L.; Qin, M.W. Relationship between climatic change and cynaobacterial bloom in Taihu Lake. *Chin. J. Ecol*. **2010**, *29*, 55–61. (In Chinese)
4. Qin, M.R.; Shang, Z.T.; Ren, J.; Xia, Y. Analysis of blue-green algae in Taihu Lake monitored by satellite in 2007. *J. Anhui Agric. Sci.* **2007**, *36*, 14258–14259. (In Chinese)
5. The State Council (SC). *Control Program for Water Pollution in Dianchi Lake Basin (2006–2010)*; SC: Beijing, China, 2008. (In Chinese)
6. The State Council (SC). *Control Program for Water Pollution of Chaohu Lake basin (2006–2010)*; SC: Beijing, China, 2008. (In Chinese)
7. The State Council (SC). *General Planning for Comprehensive Water Treatment in the Taihu Lake Basin*; SC: Beijing, China, 2008. (In Chinese)
8. Xu, Q.G.; Cao, J.L.; Gao, R.T.; Ding, J.T.; Jiang, L.; Zhang, H.; Jiang, T.T. Trend of Water Quality Deterioration and Eutrophication Control Phases Partition in China. *Environ. Sci. Technol*. **2011**, *34*, 147–151. (In Chinese)
9. Chen, Y.; Liu, X.L.; Zhang, H.Z.; Zhu, J.Z.; Tan, Y.; Li, J.H. Change of water quality in Badong section of Three Georges Reservoir. *Environ. Sci. Technol*. **2005**, *8*, 40–41. (In Chinese)
10. Shi, J.P.; Li, X.; Wang, W. A study on temporal and Spatial Distribution of water Quality based on grey associative model. *Guangdong Agric. Sci.* **2012**, *4*, 111–117. (In Chinese)
11. Zhou, J.X.; Wang, J.; Wang, P.F.; Hua, Y.; Liu, B.; Li, J. Wavelet Analysis of Water Quality Changes in Dianchi Lake during the past 7a. *Procedia Earth Planet Sci*. **2012**, *5*, 280–288.
12. Chang, N.B.; Chen, H.W.; Ning, S.K. Identification of river water quality using the fuzzy synthetic evaluation approach. *J. Environ. Manag*. **2001**, *63*, 293–305.
13. Yi, F.X.; Li, J.S. Application of fuzzy massing analysis to demarcation of water environment. *Environ. Sci. Technol*. **2003**, *26*, 39–40. (In Chinese)
14. Li, X.; Liu, C.F.; Zhu, X.H.; Xie, X. Comprehensive evaluation of Sea water quality based on BP network. *Mar. Sci. Bull*. **2003**, *26*, 23–25. (In Chinese)
15. Feng, Y.G. Application of matter element method to evaluating ground water quality. *Hydrol* **1995**, *4*, 54–56. (In Chinese)
16. Chen, X.H.; Jiang, T.; Chen, J.H. *Water Environment Assessment and Planning*; Sun Yat-sen University Press: Beijing, China, 2001.
17. Brazner, J.C.; Danz, N.P.; Trebitz, A.S.; Niemi, G.J.; Regal, R.R.; Hollenhorst, T.; Host, G.E.; Reavie, E.D.; Brown, T.N.; Hanowski, J.M.; *et al*. Responsiveness of Great Lakes wetland indicators to human disturbances at multiple spatial scales: A multi-assemblage assessment. *Great Lakes Res*. **2007**, *33*, 42–66.
18. Maja, C.; Patricia, C.F. Use of ecological indicators to assess the quality of Great Lakes coastal wetlands. *Ecol. Indic*. **2011**, *11*, 1609–1622.
19. Danz, N.P.; Niemi, G.J.; Regal, R.R.; Hollenhorst, T.; Johnson, L.B.; Hanowski, J.M.; Axler, R.P.; Ciborowski, J.J.H.; Hrabik, T.; Brady, V.J.; *et al*. Integrated measures of anthropogenic stress in the U.S. Great Lakes basin. *Environ. Manag.* **2007**, *39*, 631–647.
20. Morrice, J.A.; Danz, N.P.; Regal, R.R.; Kelly, J.R.; Niemi, G.J.; Reavie, E.D.; Hollenhorst, T.; Axler, R.P.; Trebitz, A.S.; Cotter, A.M.; *et al*. Human influences on water quality in Great Lakes coastal wetlands. *Environ. Manag*. **2008**, *43*, 347–357.

21. Reckhow, K.H. Empirical Models for Trophic State in Southeastern U.S. Lakes and Reservoirs. *Water Resour. Bull*. **1988**, *24*, 723–734.
22. Arman, H.; Ileri, R.; Dogan, E; Eren, B. Investigation of Lake Sapanca water pollution, Adapazari, Turkey. *Int. J. Environ. Stud*. **2009**, *66*, 547–561.
23. Kazi, T.G.; Arain, M.B.; Jamali, M.K.; Jalbani, N.; Afridi, H.I.; Sarfraz, R.A.; Baig, J.A.; Shah, A.Q. Assessment of water quality of polluted lake using multivariate statistical techniques: A case study. *Ecotoxicol. Environ. Saf*. **2009**, *72*, 301–309.
24. Zhao, Y.; Yang, A.H.; Li, Y.X. Investigation of water pollution in Baiyangdian Lake, China. *Procedia Environ. Sci*. **2010**, *2*, 737–748.
25. Zhao, L.; Zhang, X.L.; Liu, Y.; He, B.; Zhu, X.; Zou, R.; Zhu, Y.G. Three-Dimensional hydrodynamic and water quality model for TMDL development of Lake Fuxian, China. *J. Environ. Sci*. **2012**, *24*, 1355–1363.
26. Liang, D.H.; Jiang, H.H. Unifying and improving the comprehensive assessment methods of river water quality. *Environ. Monit. China* **2002**, *18*, 63–66. (In Chinese)
27. EPA. Integrated Water Quality Monitoring and Assessment Report Guidance. Available online: http://water.epa.gov/lawsregs/lawsguidance/cwa/tmdl/2002wqma.cfm (accessed on 4 June 2014).
28. EPA. Water quality assessment of Prairie Creek Reservoir in Delaware County, Indiana. Available online: http://www.freepatentsonline.com/article/Proceedings-Indiana-Academy-Science/193735307.html (accessed on 4 June 2014).
29. EPA. Quality of America's Lakes. Available online: http://water.epa.gov/type/lakes/quality.cfm (accessed on 4 June 2014).
30. Jonnalagadda, S.B.; Mhere, G. Water quality of Odzi River in the eastern highlands of Zimbabwe. *Water Res.* **2001**, *35*, 2371–2926.
31. Pesce, F.S.; Wunderlin, D.A. Use of water quality indices to verify the impact of Cordoba City (Argentina) on Suquia River. *Water Res*. **2000**, *34*, 2915–2926.
32. Zhang, Q.; Wu, Z.; Zeng, G.M.; Zhang, S.F.; Fang, Y.; Xiao, X.C.; Yuan, Q.S. Temporal-spatial change of aquatic environment in Hunan Province. *Environ. Sci. Technol*. **2008**, *31*, 98–102. (In Chinese)
33. Tong, L.P. *General Environmental Science*; Higher Education Press: Beijing, China, 1997. (In Chinese)
34. Kannel, P.R.; Lee, S.; Lee, Y.S.; Kannel, S.R.; Khan, S.P. Application of Water Quality Indices and dissolved oxygen as indicators for river water classification and urban impact assessment. *Environ. Monit. Assess*. **2007**, *132*, 93–110.
35. Kocer, M.A.T.; Sevgili, H. Parameters selection for water quality index in the assessment of the environmental impacts of land-based trout farms. *Ecol. Indic*. **2014**, *36*, 672–681.
36. State Environmental Protection Administration of the People's Republic of China (SEPA). *Environmental Quality Standards of Surface Water (GB3838–2002)*; SEPA: Beijing, China, 2002. (In Chinese)
37. Xie, G.J.; Zhang, J.P.; Tang, X.M.; Cai, Y.P.; Gao, G. Spatio-temporal heterogeneity of water quality (2010–2011) and succession patterns in Lake Bosten during the past 50 years. *J. Lake Sci*. **2011**, *23*, 837–846. (In Chinese)
38. Li, R.; Zhang, Y. Analysis of spatial and temporal variation of water quality and its influencing factors in Poyang Lake. *Water Resour. Prot*. **2011**, *27*, 9–18. (In Chinese)

39. Ren, W.; Zhong, Y.; Meligrana, J.; Anderson, B.; Watt, W.E.; Chen, J.; Leung, H.L. Urbanization, land use, and water quality in Shanghai: 1947–1996. *Environ. Int.* **2003**, *29*, 649–659.
40. Yin, Z.Y.; Walcott, S.; Kaplan, B.; Cao, J.; Lin, W.; Chen, M.J.; Liu, D.S.; Ning, Y.M. An analysis of the relationship between spatial patterns of water quality and urban development in Shanghai, China. *Comput. Environ. Urban. Syst*. **2005**, *29*, 197–221.
41. National Bureau of the People's Republic of China. Available online: http://www.stats.gov.cn/ (accessed on 2 May 2014).