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Three decades of changes in water environment of a large freshwater Lake and its relationship with socio-economic indicators

Cuicui Li[1,2,3], *Weiying Feng*[3,*], *Fanhao Song*[3], *Zhongqi He*[4], *Fengchang Wu*[1,3], *Yuanrong Zhu*[3], *John P. Giesy*[3,5], *Yingchen Bai*[3]

1. *Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China*
2. *University of Chinese Academy of Sciences, Beijing 100049, China*
3. *State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China*
4. *USDA-ARS, Southern Regional Research Center, New Orleans LA70124, USA*
5. *Department of Biomedical Veterinary Sciences and Toxicology Centre, University of Saskatchewan, Saskatoon SKS7N 5B3, Canada*

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ABSTRACT

Tai Lake (Ch: *Taihu*) has attracted international attention forcyanobacteria blooms. However, the drivers of cultural eutrophication, especially long-term socio-economic indicators have been little researched. The results of research demonstrate how socio-economic development affected quality of water and how it has been improved by anthropogenic activities. This study described variability in indicators of water quality in Tai Lakeand investigated thedrivers. Significant relationships existed between concentrations of annual mean total nitrogen (TN), total phosphorous (TP), chemical oxygen demand (COD) and biological oxygen demand (BOD), and population, per capital gross domestic production (GDP) and sewage discharge ($p < 0.05$). However, mechanisms causing change varied among TN, TP, COD and BOD. Before 2000, the main contributors to increases in concentrations of TN were human population, GDP and volumes of domestic sewage discharges. After 2000, discharges of industrial sewage become the primary contributor. After 1998, the regressions of annual mean TN, TP and COD on per capital GDP, population and domestic sewage discharge were reversed compared to the former period. Since 1999, an apparent inverted U-shaped relationship between environmental pollution and economic development has developed, which indicated that actions taken by governments have markedly improved quality of water in Tai Lake. The statistical relationship between BOD and per capital GDP didn't conform to the Kuznet curve. The U-shaped Kuznet curve may offer hope for the future that with significant environmental investments a high GDP can be reached and maintained without degradation of the environment, especially through appropriate management of industrial sewage discharge.

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* *Corresponding author. E-mail:* feng_weiying@126.com. (Weiying Feng).

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Introduction

Under natural conditions, lakes evolve slowly from oligotrophic to more eutrophic status, however, activities of humans, such as industrialization and urbanization can accelerate the process (Tilman et al., 2001). Eutrophication of surface waters is a serious threat to water quality and habitat environments, drinking water supplies, food webs, and the sustainability of freshwater ecosystems (Paerl et al., 2011; Paerl and Otten, 2013). As a result, environmental issues caused by eutrophication have become increasingly severe and received more attention, especially in developing countries (Bennet et al., 2001; Feng et al., 2016a, 2016b; Paerl, 2006; Pant et al., 1980). Based on environmental theory, pivotal environmental problems are actually issues of economics, which are the result of socio-economic development. For example, Grossman and Krueger developed the Environmental Kuznets Curve (EKC) and associated hypotheses, in which the inverted u-shaped relationship relates environmental pollution and economic growth (Grossman and Krueger, 1991). In China, the economy developed rapidly after the reforms of the early 1980s during which the country opened up. The accelerating development resulted in numerous water environment pollution issues that impeded sustainable development of the social economy. It has been suggested that population growth, climate change, regulatory standards, temporal and spatial scales of project planning, socio and environmental considerations, and transboundary considerations all contribute to the intricacy of water environment problems (Simonovic, 2000; Huang et al., 2006; Kaczor et al., 2017). In the meantime, it is generally believed that water resources are more scarce in developed areas with relatively high population density (Rijsberman, 2006). So, water environment quality in those population-dense countries/areas of the world is of particular concern in order to keep balance between water resources and growing populations, gross domestic production (GDP), agricultural irrigation and urban development.

Although a multitude of theories and methods have been proposed to deal with poor quality lake water, there have not been substantial improvements (Krausfeldt et al., 2017). Numerous studies have shown that overwhelming ecological pressures from frequent and intense socio-economic activities can lead to deterioration of ecological functions of lakes and threaten the health of aquatic organisms (Brooks et al., 2016; Wu et al., 2003; Xie et al., 2014). Therefore, there is an urgent need to analyze ecological impacts of socio-economic activities (such as population; GDP; and industrial, agricultural, and domestic sewage) on lake environments. This is of importance for developing better remediation and management strategies for lake water environments.

It has been reported that effects of agricultural nonpoint source pollution on lake water quality have become increasingly important and outweigh point source pollution from both industrial and domestic sewage (Gao et al., 2002; Jin et al., 2006a, 2006b). Partial correlation analyses have demonstrated that, while populations greatly affected three environmental indicators (chemical oxygen demand (COD), total nitrogen (TN), total phosphorous (TP)), however, COD concentrations were mainly affected by agricultural input, TP was mainly influenced by industry emissions and TN was mainly impacted by agricultural activities (Feng et al., 2018; Jiao and Qin, 2002; Wu et al., 2001). When remote sensing and GIS technologies were applied to monitor concentrations of TN, TP, and COD that came from livestock farming, it was reported that these factors accounted for 34%, 58%, and 61% of the total pollution sources (Liu et al., 2010). Under effects of industrial point sources and nonpoint source pollution, it was demonstrated that water quality indicators exhibited several development stages where anthropogenic activities and aquatic environments acted as mutual constraints in the Tai Lake ecosystem (Liu et al., 2016; Wu et al., 2013; Xie et al., 2001). However, these studies mainly focused on qualitative analysis without detailed support for analysis of data. Moreover, the time spans studied in those researches were relatively short and thus, unable to comprehensively research evolution of lake water environments so as to investigate relationships between indicators of environmental health and socio-economic factors (Wang et al., 2011; Yu et al., 2012). Therefore, in this study, long-term data on key environment indicators (TN, TP, *Chlorophyll-a* (Chl-*a*)), COD, and biological oxygen demand (BOD)) and socio-economic factors (population; GDP and industrial, agricultural, and domestic sewage) were collected for Tai Lake over a period of 32 years (1980–2012). The major socio-economic factors that influenced the Lake were identified *via* quantitative analysis of the correlation between them. Finally, some suggestions for remediation and improvement of aquatic environment in Tai Lake are provided.

1. Materials and methods

1.1. Study region

Tai Lake is the third largest freshwater lake in China and is located in a subtropical monsoon zone with prevailing southeast wind in summer and northwest wind in winter, near the Yangtze River Delta between 30°56′N and 31°32′N and 119°54′E and 120°36′E with a mean depth of 1.9 m, a volume of 4.4 km^3, an area of 2338 km^2, and a catchment area of 36,500 km^2 (Li et al., 1994; Qin et al., 2010b). Mean annual outflow of Tai Lake is 7.5×10^9 m^3 and its water storage capacity is 4.4×10^9 m^3. The drainage basin involves two major provinces (Jiangsu and Zhejiang) and Shanghai Municipality (Yu et al., 2013). Shanghai is located downstream of Tai Lake. The population density is approximately 1500/km^2, more than 10-fold greater than the national average (Yu et al., 2013). Tai Lake provides important ecosystem services such as agriculture, flood protection, fishing, tourism, and shipping, and is also a repository for considerable point-source and non-point source sewage from urban areas and nearby agricultural and industrial sources due to the rapidly growing local economy (Qin et al., 2010b).

1.2. Data collection and processing

Historical water quality data from 1980 to 2012 (TN, TP, Ch1-*a*, COD, and BOD) were collected from various sources. Data for 1980–2000 were gathered from the document of “Bulletin on water resource quality of provincial water bodies in Tai Lake and surrounding rivers in the southeastern region", which can be downloaded from the website of the Tai Lake Authority of the Ministry of Water Resources and the UN "Global Environment Monitoring System" Water Programme (GEMS/Water), and data for 2000–2012 were from the "National Ecosystem Research Network of China" (Qin et al., 2010b).

Socio-economic indicators such as population, GDP, *etc*., were gathered from the Statistical Yearbook of the provinces and municipalities within the basin, Wastewater discharge such as agricultural and industrial sewage data, were collected from either the local Statistical Yearbooks or the National Environment Statistical Yearbook. Provincial statistical data were first transformed into drainage basin data by multiplying the ratio of the provincial area covered by the basin of Tai Lake to the entire provincial area calculated with a GIS tool (Arcview 3.3), and then individual provincial values were summed to obtain the socioeconomic data for the entire drainage basin of Tai Lake (Yu et al., 2013). In calculation of the population, GDP, and wastewater discharge in the basin of Tai Lake, Zhejiang and Jiangsu Provinces (Xin and Stone, 2010), which are located upstream of Tai Lake, impose greater influences on the water environment than downstream regions. Therefore, data from the upstream regions of Tai Lake were collected, whereas cities located downstream of the lake, such as Shanghai, which have no direct impact on the lake were disregarded.

Statistical analyses were conducted using EXCEL2010, MATLAB2007, and SPSS 17.0 software (at 0.01 confidence intervals). Time series trend analyses were tested using the non-parametric Mann–Kendall method in MATLAB. Correlation and regression analyses were used to reveal relationships between environmental and socio-economic indicators.

2. Results

2.1. *Temporal trends of nutrients in Tai Lake*

From 1980 to 2012, there are a significant linear relationships between water quality indicators (TN, TP, Ch1-*a*, COD, and BOD) and time, for which, all the R^2 values are greater than 0.5 ($p < 0.01$), revealing that the concentrations of water quality indicators were increasing (Fig. 1). Mean annual concentrations of TN increased significantly with fluctuations from 1980 to 2004, followed by intermittent small-magnitude decreases from 2004 to 2010 and increased again until 2012. Generally, concentrations of TN increased from 0.65 mg/L in 1980 to 2.7 mg/L in 2012, more than quadrupling in 32 years. During the study period, four obvious peaks in concentrations of TN were observed in 1988, 1992, 1997, and 2004, with the greatest concentration (4.8 mg/L) in 2004. Mean annual increases were 0.084 mg/L. However, this varied for different time intervals. From 1980 to 1990, the mean annual rate of increase was 0.084 mg/L, rising to 0.13 mg/L during 1990–2000 and reaching the greatest value of 0.448 mg/L in 2004. Following that, concentrations of TN decreased at a rate of 0.26 mg/L until 2012. Mean concentrations of TN were 1.6 mg/L, 2.8 mg/L, and 3.6 mg/L, during the 1980s (1980–1990), 1990s (1990–2000) and 2000s (2000–2012), respectively. The Mann-Kendall trend analysis revealed that concentrations of TN increased continuously throughout the 32 years considered during this study, without any sharp transitions (Table 1).

During 1980–2012, concentrations of TP increased with some fluctuations, from 0.03 to 0.13 mg/L (4.33-fold), a magnitude of change that was similar to that of TN (Fig. 1). Although concentrations of TP exhibited an overall increasing trend, there were still some intermittent decreases during 1987–1992, 1997–1998, and 2008–2012. Four peak concentrations of TP were observed in 1987, 1997, 2002, and 2008. The greatest concentration of TP was 0.175 mg/L, which was observed in 1997, whereas maximum concentration of TP in 2002 could be attributed to a decline in the volume of inflow during that year. Concentrations of TP increased annually by 0.004 mg/L during the study period. However, as for the 1980s, 1990s and 2000s, mean annual rates of increase were 0.005 mg/L, 0.005 mg/L, and 0.007 mg/L, respectively. During the period from 2008 to 2012, the rate of decrease was 0.01 mg/L. On average, concentrations of TP were 0.056, 0.09 and 0.14 mg/L in 1980–1990, 1990–2000 and 2000–2012, respectively. Results of the Mann–Kendall trend analysis suggested that there was an abrupt increase in the concentrations of TP in 1993 (Table 1).

Temporal trends in concentrations of Ch1-*a* were more complicated than those of TN and TP (Fig. 1). There were more sharp fluctuations, possibly because Ch1-*a* was significantly affected by multiple factors, such as temperature, N/P ratio, sunlight and nutrient availability. During 1980–2012, Ch1-*a* demonstrated a fluctuating and increasing trend, increasing from 0.004 to 0.022 mg/L (5.5-fold increase). There were also multiple intermittent decreases. The peak concentration of Chl-*a* (0.029 mg/L) was observed in 2008. The mean rate of increase in Chl-*a* during the 32-year period was 0.0007 mg/L. In the 1980s, late 1990s and 2000s, concentrations of Chl-*a* were 0.005 mg/L, 0.011 mg/L, 0.02 mg/L. Results of the Mann-Kendall trend analysis revealed a sudden increase in concentrations of Chl-*a* in 1997 (Table 1).

Overall, the temporal trends of COD in Tai Lake were relatively stable. The concentration of COD increased from 2.8 to 4.9 mg/L during the study period, demonstrating a 1.73-fold increase with an average annual rate of increase of 0.083 mg/L. During 1980–1993, COD increased 43%, followed by a significant decreasing trend from 1993 to 1995, then again increased between 1995 and 2008. After 2008, the COD again decreased until 2010, followed by another increase between 2010 and 2012. Mean concentrations of COD were 3.4 mg/L, 4.5 mg/L and 5.3 mg/L during the 1980s, 1990s, and 2000s, respectively. The Mann–Kendall trend analysis revealed an abrupt increase in 1991 (Table 1).

During the period of 1980–2012, the BOD in Tai Lake increased from 1.5 to 3.0 mg/L, which was approximately a 2-fold increase. Between 1980 and 1982, a significant increase was observed, followed by a decrease in 1983, and then followed by a period of fluctuation and general increasing trend during 1983–2004. In 2004, it reached a peak of 3.8 mg/L. BOD then exhibited a decreasing trend until 2010 followed by an increase from 2011 to 2012. Mean concentrations of BOD were 1.3, 1.8 and 2.9 mg/L in the 1980s, 1990s and 2000s, respectively, with a mean annual increase rate of 0.068 mg/L over the entire study period. The Mann–Kendall trend analysis revealed a turning point of increase in 1996 (Table 1).

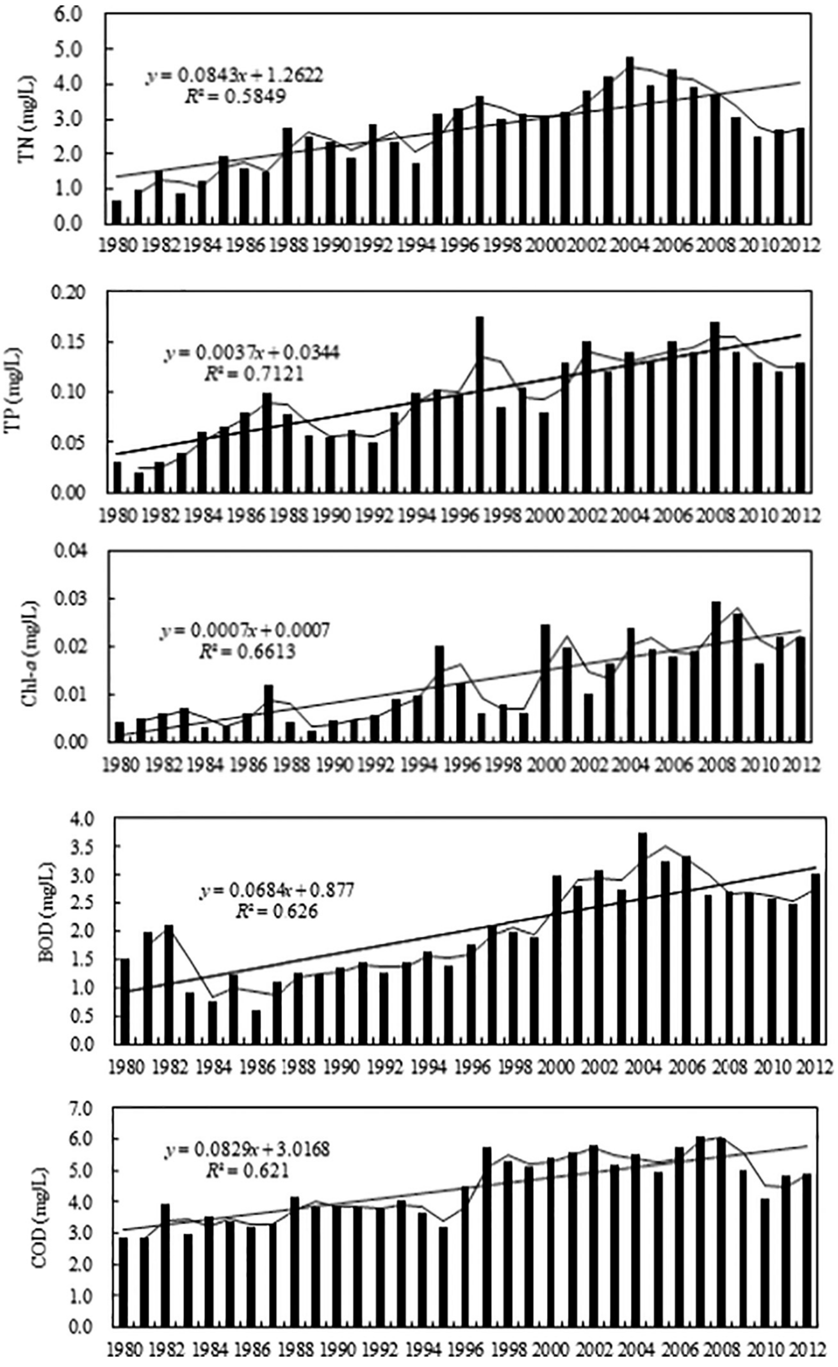

Fig. 1 – Temporal trends of water quality indicators in Tai Lake.

2.2. Temporal trends of socio-economic indicators in Tai Lake

During the study period, GDP in the Tai Lake basin increased from 9.396×10^{10} to 1.017×10^{12} CNY, increasing 11-fold with an annual average increase rate of 8.2% (Fig. 2). In the 1980s, the mean annual rate of increase was 13.1%. In the 1990s, as the economic development accelerated, the mean annual rate of increase was as great as 20.7%, which was 7.0% greater than that of the previous decade. In the 2000s, economic development slowed compared to the 1990s. This resulted in a reduction in the rate of growth to 17.0%, which was still 4% greater than that of the 1980s.

Since the 1980s, the Tai Lake basin has experienced rapid economic growth, accompanied by continuous improvement in the quality of life for the residents and rapid growth of the human population, which increased from 14.4 million in 1980 to 18.71 million in 2011. This represents a net increase of 4.31 million people, with a mean annual rate of increase of 8% (Fig. 2). Also, due to increasing population as well as improved standard of living, from 1980 to 2012 domestic sewage has

Table 1 – Test results for the mutational years of water quality indicators in Tai lake.

Indicators	TN	TP	COD	BOD	Chl-*a*
Tendency	–	increase	increase	increase	increase
Years of mutation	–	1993	1991	1996	1997

TN: total nitrogen; TP: total phosphorous; COD: chemical oxygen demand; BOD: biological oxygen demand; Chl-*a*: *Chlorophyll-a*.

increased from 9.7×10^{10} to 8×10^{11} kg. In all, the domestic sewage discharge has increased 8-fold with a mean annual rate of increase of 7.1%.

Due to accelerated economic development in the early 1990s, during the period of 1985–2011, discharges of industrial sewage increased by 1.38 fold, (Fig. 2). owing to the accelerated economic development in the early 1990s. There was a turning point in 1998 with the minimum value of less than 400 million tons. After that time, releases of industrial wastes increased dramatically until 2012. However, the increase rate after 1998 seemed to not match those of population and GDP growth. This might be attributed to a series of mandatory measures implemented by the government, reinforced management of enterprise sewage treatment technologies and innovation of industrial technologies.

3. Discussion

3.1. *Influence of anthropogenic activities on the water quality of Tai Lake*

During the 1960s, industrial development was initiated in the basin of Tai Lake, when loadings of TN and TP were less than 10,000 tons/year and 1000 tons/year, respectively (Lai and Yu, 2007). As a result, the aquatic environment of Tai Lake was in better condition such that blooms of cyanobacteria rarely occurred (Qin, 2008). During the 1980s and 1990s, GDP increased by 8-fold and industrial output also increased tremendously. Meanwhile, urbanization in the basin of Tai Lake increased from 35.5% in 1980 to 66.5% in 2000 (Jin et al., 2006a, 2006b), which resulted in increased discharges of industrial and domestic wastewater to the lake. In the 1980s, concentrations of water quality indicators in Tai Lake increased synchronously with the rapid economic growth in the basin (Fig. 3). Spatial and seasonal distribution of water quality indicators in Tai Lake corresponded with nutrient loads from the major adjoining tributaries, which suggested that changes in concentrations of nutrients in the lake were due, primarily to exogenous loading (Li et al., 2011). According to the classification proposed by Forsberg and Ryding (1980), Tai Lake was oligotrophic in 1960, but by 1981 it had become mesotrophic and by 1987 was eutrophic. After 1990, the deterioration of water quality in Tai Lake has accelerated. This can be confirmed by increased frequency of occurrence of blooms of algae, primarily cyanobacteria, increased from occurring two or three times during the mid- to late 1980s to four or five times during the middle and late 1990s and gradually expanded to encompass most of the lake (Qin, 2008). The rapid increases in concentrations of TN, TP, Chl-*a* and COD between 1992 and 1997 further corroborated this condition.

From 1997 to 2001, concentrations of TN and TP declined significantly, whereas concentrations of COD and BOD exhibited an opposite trajectory. Declines in concentrations of TN and TP after 1996 might be explained by the reduction of external nutrient input from the catchment following regulations and monitoring imposed by the local government in 1995 (Fan et al., 2000). As a consequence, Tai Lake responded almost immediately when the external nutrient loading was reduced and nutrient concentrations declined considerably after 1996. However, these measures to control inputs of nutrients only lasted until 2001, after which wastewater discharge increased again (Qian and He, 2009). Consequently,

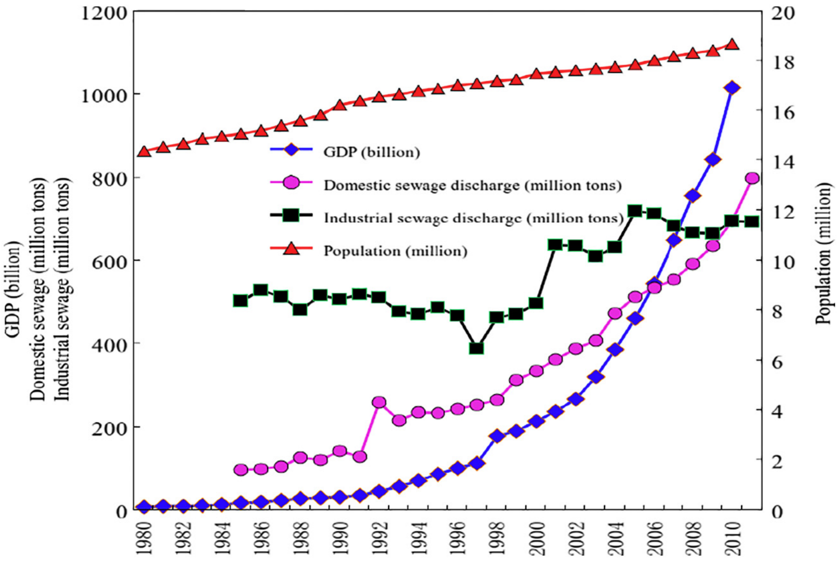

Fig. 2 – Temporal trends of economic factors in Tai Lake basin.

nutrient concentrations again increased between 2002 and 2006, despite the Chinese central and local governments transferring water from the Yangtze River in order to improve water quality in Tai Lake. These transfers had no apparent effects on reducing concentrations of TN and TP (Li et al., 2011). In May 2007, a horrible cyanobacteria bloom, which was famous all over the world, occurred in Tai Lake. This led to closure of drinking water plants in Wuxi city, which resulted in severe shortages of drinking water (Qin, 2008). Since then, the Chinese government has adopted a series of measures to reduce exogenous loading of nutrients and other contaminants to Tai Lake. These included, shutting off the flow of the Liangxi River from Meiliang Bay, closing a number of polluting factories, and building additional wastewater treatment plants (Yu et al., 2013). Current annual external loads have decreased significantly. These methods improved water

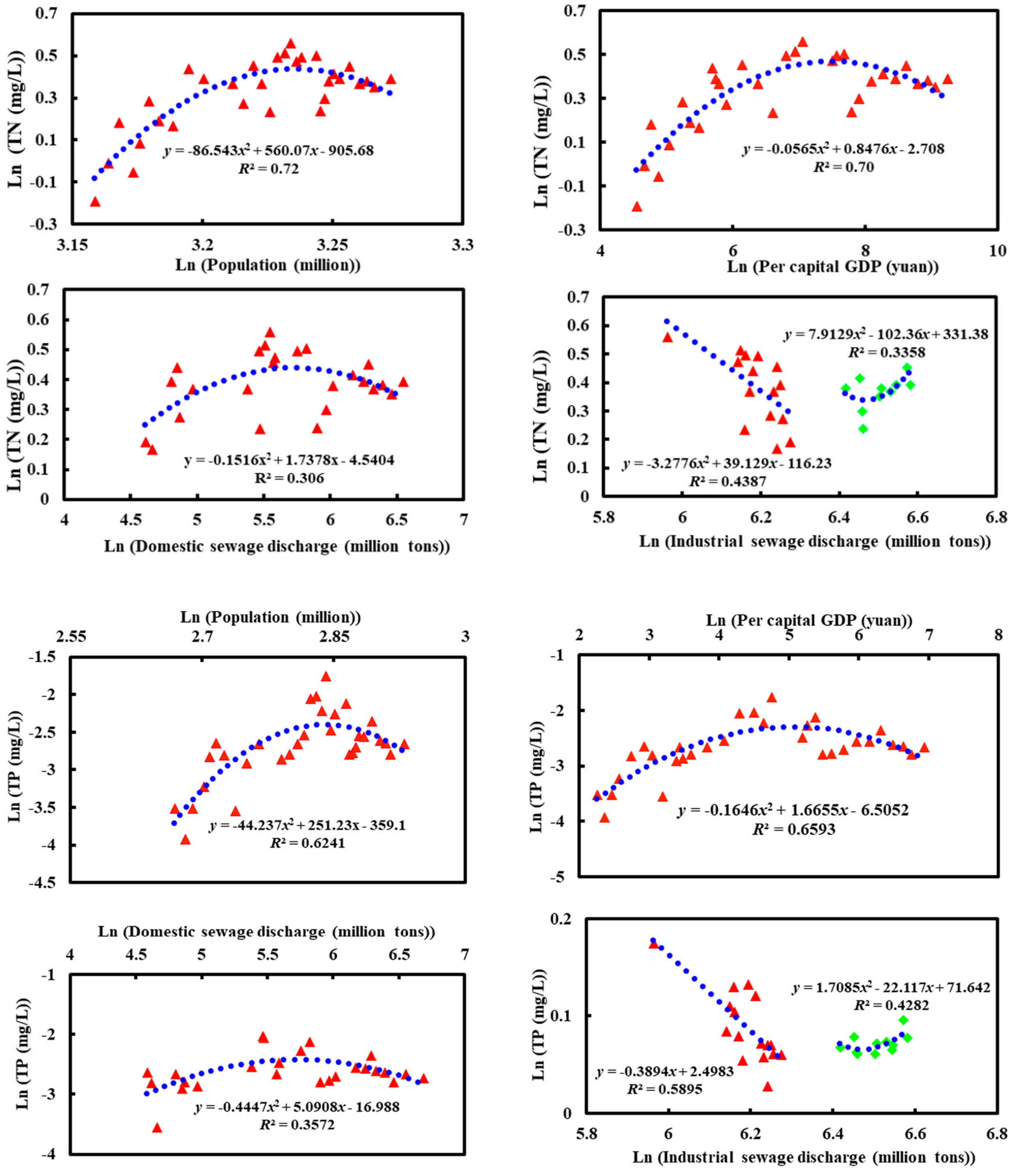

Fig. 3 – Relationship between water quality indicators and socio-economic factors in Tai Lake basin.

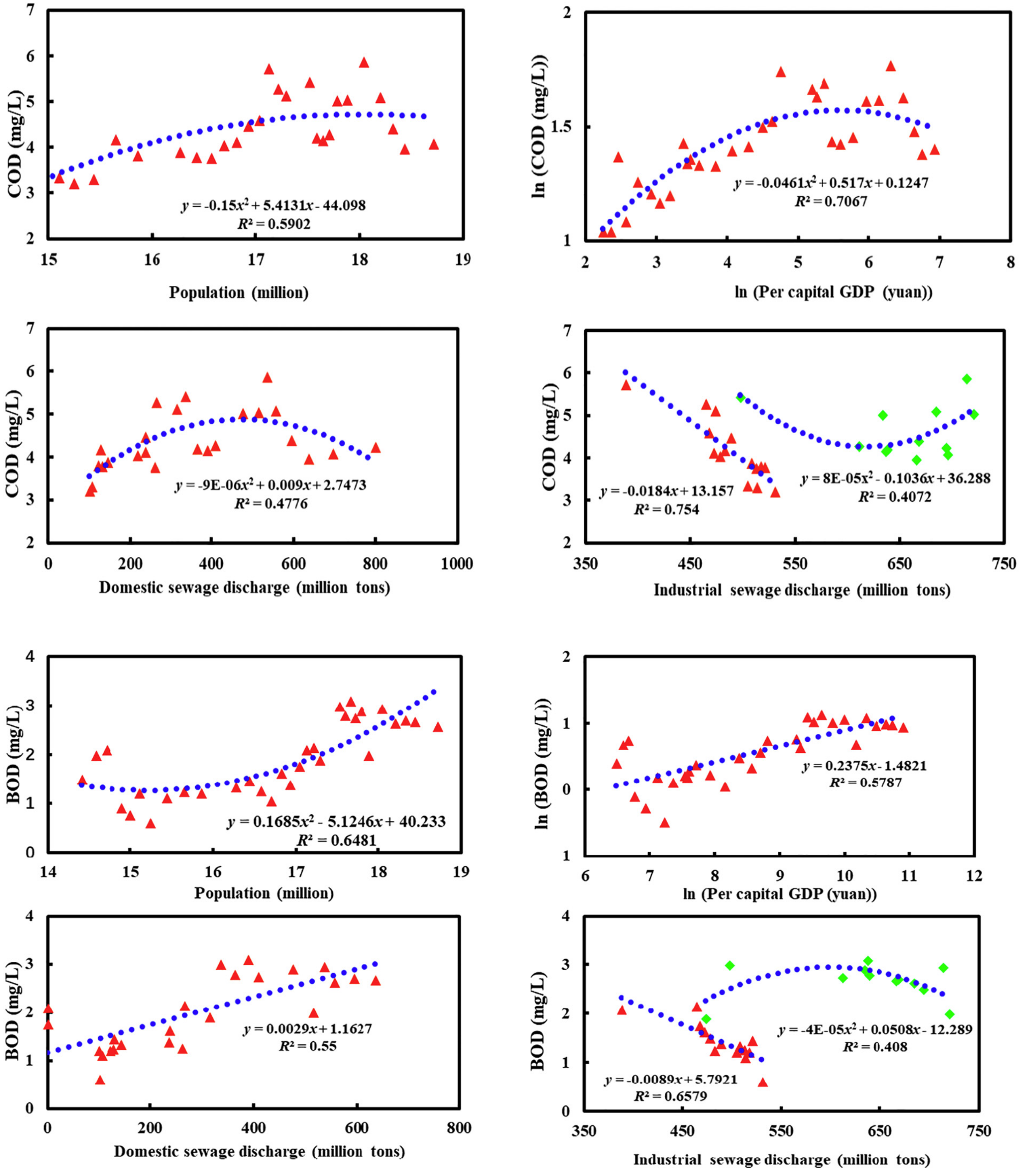

Fig. 3 (*continued*)

quality and the nutrient concentrations have decreased significantly.

3.2. *Relationships between socioeconomic indicators and water quality of Tai Lake*

Under natural conditions, the process of eutrophication of lakes from an oligotrophic state takes a long time. Industrial development was initiated in the basin of Tai Lake in 1960S (Lai and Yu, 2007). Therefore, cyanobacteria were not detrimental to ecological services provided by Tai lake (Qin, 2008). However, the current water environment in Tai Lake, characterized by greater concentrations of TN, TP, Chl-*a*, COD, and BOD, such that frequencies and durations of blooms of cyanobacteria have been greater, which has resulted in conditions that were not present historically. There is no question that these effects are due to large amounts of nutrients being input to Tai Lake (Li et al., 2000; Xiong et al., 2002; Xu et al., 2002). These loadings are the direct results of intensive anthropogenic activities in the basin that caused these nutrient indicators to be increased and altered the natural aquatic environment of Tai Lake. However, mechanisms of increases vary among TN, TP, COD and BOD. For that reason, restoration of the lake to its previous conditions will require multiple strategies.

Increased concentrations of these nutrients indicators is closely linked to the rapid development of the regional population and economic policies, especially since the 1980s (Fig.3). Statistical analysis of the historical data showed that variation in concentrations of TN was significantly associated with populations of humans, GDP, domestic and industrial sewage discharge ($p < 0.05$). All of these indicators suggest that the natural balance of nutrients in Tai Lake have been broken by anthropogenic additions derived from the socioeconomic activities. Of these, population and GDP explained as much as 72% and 70% of the variance in concentrations of TN ($p < 0.05$). This indicates that population and GDP constitute the direct dominant for concentrations of TN, TP and COD, all of which exhibited similar associations with measures of human economic activities.

The population of humans in the region surrounding Tai Lake has increased from 14.40 million in 1980 to 18.71 million in 2011, which is a net increase of 4.31 million (Fig. 2). However, concentrations of TN have not been increasing monotonically with population. There was a positive association between concentrations of TN and human population until 1998, at which point the relationship changed drastically, after which it exhibited a significant negative relationship with human population (Fig. 3). Similar trends were observed for other metrics of eutrophication, whereas, the statistical relationship between TN concentration and discharges of industrial sewage was positively related initially followed by a negative relationship. This result suggests that before 2000 the main contributors to increases of concentrations of TN were population, GDP and discharge of domestic sewage, but after 2000, discharge of industrial sewage has been the dominant contributor to increases of concentrations of TN.

Before 1998, increases in numbers of humans constituted an important source of TN. In order to support the increasing population, there had to be sufficient food and water. Therefore, in order to increase productions of crops, greater amounts of inorganic fertilizer was used on farmland, which likely was an important source of TN (Liu et al., 2014a, 2014b). Furthermore, this increase in population resulted in an increase of consumption of water from 23.4×10^9 to 31.6×10^9 m^3 with a net increase of 8.2×10^9 m^3 (Zhang, 2009). Meanwhile, urbanization has increased from 35.5% in 1980 to 66.5% in 2000 in the Tai Lake Basin (Jin et al., 2006a, 2006b). Due to this urbanization, the area of impervious ground has increased, which has prevented urban sewage from penetrating downward and resulted in a greater sewage discharged directly into Tai Lake, thereby increasing concentrations of TN and TP in Tai Lake (Yang et al., 2018). Another important determinant of input of TN has been due to economic growth, which is indicated by the significant correlation between TN concentration and GDP in the basin before 1998 (Fig. 3). GDP, which is a surrogate indicator of numbers of people as well as industrial activity, increased by 11-fold during the study period.

Discharge of industrial sewage (Liu et al., 2001; Wu et al., 2010; Zhu et al., 2015a) was negatively associated with TN, TP, COD and BOD from 1985 to the late 1990s, which might be explained, in part, by reduction of external nutrient input from the catchment due to regulations imposed by local governments in 1995 (Fan et al., 2000). All the industries in the catchment, especially those in the countryside, were forced to control waste water discharges. No untreated wastewater was allowed to discharge to the rivers in the Tai Lake basin. In 1998, the State Council organized the “zero point action”, which was aimed at controlling industrial pollution and banning the use of phosphorous detergents in the Tai Lake Basin. As a consequence, TN and TP concentrations decreased meanwhile. However, after 2000, significant positive relationships were

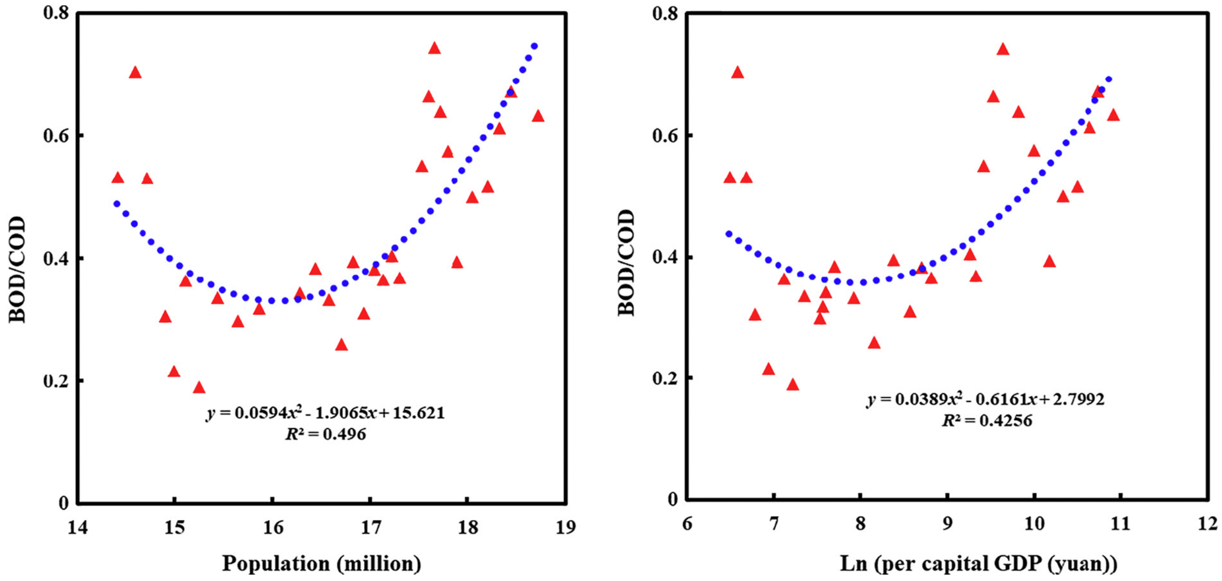

Fig. 4 – Relationship between sewage biodegradability and socio-economic indicators in Tai Lake basin.

Table 2 – Relationship between water quality indicators in Tai Lake.

Indicators	TN	TP	Chl-*a*	COD	BOD
TN	1	0.785**	0.600**	0.856**	0.740**
TP	0.785**	1	0.688**	0.804**	0.677**
Chl-*a*	0.600**	0.688**	1	0.602**	0.745**
COD	0.856**	0.804**	0.602**	1	0.793**
BOD	0.740**	0.677**	0.745**	0.793**	1

TN: total nitrogen; TP: total phosphorous; COD: chemical oxygen demand; BOD: biological oxygen demand; Chl-*a*: *Chlorophyll-a*.
** correlation is significant at the 0.01 level (2-tailed).

found between annual mean TN, TP and industrial sewage discharge ($p < 0.05$). This may be attributed to the adjustment of industrial structure which took place in Tai Lake basin after 2000.

The regressions of annual mean TN, TP and COD on per capital GDP, population and domestic sewage discharge after 1998 were opposite from what they had been during earlier periods. Concentrations of TN, TP and COD were negatively correlated with population and per capital GDP. The turning point that occurred in 1998 indicated that under measures in controlling nutrient inputs, a Kuznet curve appeared. This relationship suggested that environmental quality deteriorates during periods when economic growth is increasing, but still at a relatively low level. However, as per capita income improves such that basic needs are being met, expectations of the populous for the future increase demands on government to provide a better environment also increases (Arik, 2001). The turning point in Tai Lake appeared when the per capital GDP was 10,383 yuan. After that time, investments in environmental protection and restoration increased significantly (Zhou et al., 2017). This is particularly true for Tai Lake since the later 1990s as a large amount of sewage treatment plants were built and have been operated at a high level of efficiency (Yu et al., 2013). The inverted U-shaped relationship (Fig. 3) between environmental pollution and economic development indicate that environmental protective actions financed by the government have markedly improved the water environment (Liu et al., 2008; Ouyang et al., 2016). However, maintaining current quality or further improving water quality in Tai Lake will take constant vigilance. First, the turning point of TN and TP only indicated that there was a favorable turn for the contamination status in Tai Lake, which is still far worse than what it was during the 1970s and 1980s. Second, some authors have suggested that the Kuznets curve, which is often observed, is not always the case and the relationship between economic growth and resources and environment is not necessarily the case without mutual competition (Al-Mulali et al., 2015). Therefore, environmental managers should be more cautious in using this curve as an indicator of what is possible.

The sources of COD are almost the same as for TN and TP and its increase was also significantly correlated with growth of the human population ($p < 0.05$) and GDP ($p < 0.05$) in the basin (Fig. 3). However, there were some dissimilarities in relationships with BOD. First, BOD had a significantly positive relationship with population without a turning point until 2010. Second, the statistical relationship between BOD and per capita GDP did not conform to the Kuznets curve as did the other environmental indicators. BOD increased dramatically with industrial sewage discharge after 2000 whereas concentrations of TN, TP and COD decreased. There may be some explanations for this. For instance, BOD is an important indicator of the degree of organic pollution in water bodies, which is indirectly represented by the amount of dissolved oxygen consumed by microbial metabolism. Before the 1980s, the deterioration of water quality, mainly evident in TN and COD, was closely linked to primary industries (agricultural development), when pesticide application in the basin was 2.4 times that of the national average (Chen et al., 2010). Afterwards, BOD has replaced these as the foremost indicator of deteriorating water quality (Li et al., 2000; Zhu et al., 2013, 2015b) owing to the urbanization and the transformation of primary industries to secondary and tertiary industries, as well as the consequent increase in living standards in the basin (Qin, 2008). This can be further illustrated by Fig. 4, which shows that sewage biodegradability increased evidently with population and per capita GDP from 1995 on. On the other hand, in addition to external discharges, the life cycles of phytoplankton (growth, death, and degradation) can also contribute greatly to the increase of BOD in Tai lake (Wu et al., 2011) as indicated by Table 2, which shows that BOD and Ch1-*a* were significantly correlated ($r = 0.745$, $p < 0.01$).

4. Conclusions

Results of the study reported here demonstrate that the indicators of water quality in Tai Lake, including TN, TP, COD and BOD are significantly correlated with population, GDP and sewage discharge ($p < 0.05$). However, mechanisms of change varied among them. Before 2000, the main contributors to concentrations of TN were population, GDP and discharges of domestic sewage. After that date, discharges of industrial wastes became the main contributors to concentrations of TN in Tai Lake. The regressions of annual mean TN, TP and COD on per capita GDP, population and discharge of domestic sewage after 1998 were opposite of what they had been during earlier periods of economic development. Since 1999, there has been an inverted U-shaped relationship between environmental pollution and economic development, which highlighted how government-financed environmental protective actions have markedly improved the water environment. Unlike other indicators of water quality, statistical relationships between BOD and per capita GDP did not conform to the Kuznet curve. This was due to urbanization and a transformation to other kinds of industries as well as increases in standards of living in the basin.

The U-shaped Kuznet curve is useful to offer hope for the future that with significant environmental investments, a high GDP can be reached and maintained without the continued expense to the environment, while simultaneously restoring and preserving natural aquatic freshwater ecosystems, especially through appropriate management of discharges of industrial wastes.

Acknowledgments

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