sustainability

MDPI

Article

Spatio-Temporal Distribution of Total Nitrogen and Phosphorus in Dianshan Lake, China: The External Loading and Self-Purification Capability

Guohua Xiong [1,2], Guochen Wang [1,2], Dongqi Wang [1,2,*], Weilin Yang [1,2], Yuanyuan Chen [1,2] and Zhenlou Chen [1,2]

1 Key Laboratory of Geographic Information Science (Ministry of Education), East China Normal University, Shanghai 200241, China; xgh2008@163.com (G.X.); Dustran@126.com (G.W.); 18017597081@163.com (W.Y.); yychen@re.ecnu.edu.cn (Y.C.); zlchen@geo.ecnu.edu.cn (Z.C.)

2 School of Geographical Sciences, East China Normal University, Shanghai 200241, China

* Correspondence: dqwang@geo.ecnu.edu.cn; Tel.: +86-21-5434-1201

Academic Editor: Vincenzo Torretta

Received: 10 January 2017; Accepted: 23 March 2017; Published: 27 March 2017

Abstract: In this article, long-term data, statistical analysis, and spatial interpolation method were applied to the analyses of the spatial and temporal changes of total nitrogen (TN) and total phosphorus (TP) in Dianshan Lake. We also estimated the self-purification capability of TN and TP in Dianshan Lake. The results showed that interannual variability of the average concentration of TN in Dianshan Lake changed significantly, showing a characteristic increase before a decline, and the average concentration of TN showed an obvious downward trend, especially after 2007. Interannual variability of the average concentration of TP in Dianshan Lake fluctuated, and the average concentration of TP showed a downward trend after 2007. The seasonal variations of TN and TP in Dianshan Lake were similar. Higher TN concentration occurred in winter and spring, while higher TP concentration appeared in summer, autumn, and winter. The spatial distribution of TN and TP in Dianshan Lake were similar, showing a characteristic which decreased from north to south and west to east. The highest TN and TP values were mainly distributed in the inlet monitoring sites, while the lowest TP values were distributed in the outlet monitoring sites. The self-purification capability of TN and TP were about 2289.97 t/yr and 112.16 t/yr, which suggested a deterioration of natural water quality. Our research showed that Dianshan Lake was highly eutrophic and that water quality showed a substantial improvement from 1996 to 2015.

Keywords: interannual variability; spatio-temporal distribution; self-purification capability; Dianshan Lake

1. Introduction

As an important part of wetlands, lakes play vital roles in regulating runoff, providing water, purifying water quality, regulating regional climate, recording the change of the regional environment, maintaining the regional ecological balance system, and the reproductive function of biodiversity [1–3]. Water pollution caused by organic matter is a major global issue which requires more attention [1,4–9]. Many studies are focused on the treatment and management of water pollution—especially in reducing nutrient loading and eutrophication, such as algal blooms in rivers and lakes [6,10–12].

Lake self-purification capacity is the capability by which lakes are enabled to dilute, lessen, or eliminate the undesirable effects of entered pollutants [13–16]. The self-purification of natural water systems is a complex process that often includes interactions and mutual influences among physical, chemical, and biological processes. Due to this complex process, water (rivers or lakes) can recover its original state [7].

Quantities of nutrient loading (N and P) have contributed to the intensive eutrophication of Dianshan Lake, decreasing water clarity and water quality, causing harmful algal blooms and biomass losses, and breaking the balance of the regional ecological system and the reproductive function of biodiversity [13,17]. Previous studies have pointed out that algal blooms frequently occur in shallow lakes, and most cases of lake eutrophication are caused by excessive nutrient (e.g., N, P) inputs [6,18]. Other lakes in China have similar issues of nutrient overloading, such as Taihu Lake, Gehu Lake, and Chaohu Lake [19–22]. Hence, water monitoring and evaluation are extremely necessary for lakes. Short-term water quality monitoring data reflect the changes in a lake's ecological environment within a certain time, but it cannot reflect the long-term evolution process of the lake environment [14,17]. As an approach, long-term data analysis has unique merits for the detection of long-term trends with seasonal fluctuations and for the quantification of changes in these parameters between two historic periods. A number of studies on lake restoration have shown that long-term data analysis is a reliable and practical tool and is superior in obtaining a sufficient overview of all possible environmental parameters [14,23,24].

Dianshan Lake is a shallow lake located in Taihu Lake Zone, influenced by the waste water released by agriculture and residents. It has had several water pollution issues (algal blooms) in the last 20 years, and its water quality has drawn more attention [3,23,25]. However, to our knowledge, few studies have been focused on the study of the self-purification capacity of Dianshan Lake, as it is very difficult to determine the dominant parameters or factors which have significant influences on the estimation of water self-purification capacity [12,13]. Dianshan Lake is not only the drinking water source for Shanghai's people, but also plays vital roles in transportation, agricultural farm irrigation, aquaculture, impounding control, flood discharge, and so on. Here we use a 20-year observation conducted from 1996 to 2015. The monthly concentration of nitrogen and phosphorus in Dianshan Lake was investigated to study the spatial and temporal changes of TN and TP in the lake. Moreover, we also calculated the self-purification capability of TN and TP in Dianshan Lake.

2. Materials and Methods

2.1. Study Location and Monitoring Sites

Dianshan Lake (120°53′–121°01′E, 31°04′–31°12′N) is located on the border of Jiangsu Province and Shanghai in East China, and it is an alternately inflow–outflow lake in the Taihu Lake Zone, with an average depth of 2.1 m, a maximum water depth 3.6 m, and a surface water area of 62 km^2 [25] (Figure 1). Dianshan Lake is the largest freshwater lake in Shanghai, with a relatively short stagnation time, and the hydraulic retention time is approximately 29 days. Dianshan Lake receives water mainly from Taihu Lake via Jishui Port, Dazhushe, and other harbors from northwest to southeast, and then discharges into the Huangpu River through Lanlu Port, Dianpu River, and other rivers. The water from Dianshan Lake flows gently, and the water flow rate into Dianshan Lake is approximately 0.03 m/s, decreasing from near the shore to the center of the lake. S1, S2, S3, and S4 are the major inlets that contribute most of the total water discharge into the lake, with the water yield of 6%, 40%, 25%, and 29% of the total water inflows, respectively [26,27]. S12 and S13 are the main outlets of Dianshan Lake, with water yields of 13% and 74% of the total water output, respectively [26,27].

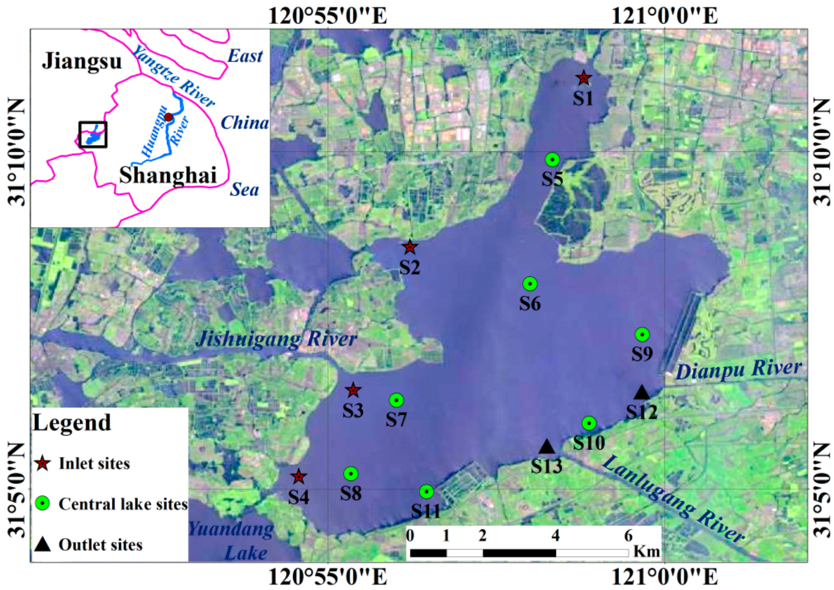

Figure 1. Monitoring sites map of Dianshan Lake.

2.2. Monitoring Data

The main water quality monitoring data for Dianshan Lake were obtained from the Shanghai Environment Protection Bureau (SEPB). There are a total of 13 monitoring sites covering Dianshan Lake, which include monthly average concentrations and annual average concentrations of total nitrogen (TN) and total phosphorous (TP) in each monitoring site, as shown in Figure 1. The concentrations of TN and TP were monitored monthly at 13 sites in Dianshan Lake from 2001 to 2015 and from 1996 to 2015, respectively. Before 2005, only the annual average concentration of TN and TP was recorded and used in this research. Monthly data of TN and TP concentrations at 13 sites from 2005 to 2015 was used for the analysis of seasonal variation. To better understand the spatial distribution of TN and TP, we divided our research area into inlet sites (IS, which include S1–S4), central lake sites (CLS, which include S5–S11), and outlet sites (OS, which include S12–S13).

2.3. Methods

To present the spatial distribution of TN and TP in Dianshan Lake, we used the inverse distance weighted (IDW) method. IDW is one of the most useful spatial interpolation methods for estimating the values of an attribute at a site by using the same attribute sampled at neighbor points [28]. IDW interpolation explicitly implements the assumption that things that are close to one another are more alike than those that are farther apart. To predict a value for any unmeasured location, IDW will use the measured values surrounding the prediction location. Those measured values closest to the prediction location will have a greater influence on the predicted value than those farther away. Thus, IDW assumes that each measured point has a local influence that diminishes with distance. It weights the points closer to the prediction location greater than those farther away, hence the name "inverse distance weighted". In this paper, the spatial variations of TN and TP in Dianshan Lake were drawn using ArcGIS 10.3 software (Esri, Redlands, CA, USA).

The general formula is:

$$\hat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i)$$

$\hat{Z}(s_0)$ is the value we are trying to predict for location s_0.

N is the number of measured sample points surrounding the prediction location that will be used in the prediction.

λ_i are the weights assigned to each measured point that we are going to use. These weights will decrease with distance.

$Z(s_i)$ is the observed value at the location s_i.

The formula to determine the weights is as follows:

$$\lambda_i = d_i^{-p} / \sum_{i=1}^{N} d_i^{-p}$$

$$\sum_{i=1}^{N} \lambda_i = 1$$

As the distance becomes larger, the weight is reduced by a factor of p.

The quantity d_i is the distance between the prediction location s_0, and each of the measured locations s_i. The power parameter p influences the weighting of the measured location's value on the prediction location's value; that is, as the distance increases between the measured sample locations and the prediction location, the weight (or influence) that the measured point will have on the prediction will decrease exponentially. The weights for the measured locations that will be used in the prediction are scaled so that their sum is equal to 1.

Pearson correlation analysis and linear regression were used to analyze the interannual variation of TN and TP from 1996 to 2015 with SPSS 19.0 (SPSS Inc., Chicago, IL, USA,), and the R^2 and p-value also presented in the results. To test seasonal variation of TN and TP, we use the paired-sample t-test with SPSS 19.0.

We also calculated the self-purification of the lake, and it was defined as follows:

$$P = Q_{in} \times C_{in} + Q_d + Q_r - Q_{out} \times C_{out}$$

where P is the self-purification capability of the lake; Q_{in} and Q_{out} stand for the water inflow and outflow, respectively; Q_d is the inputs of dry and wet atmospheric deposition; Q_r is the TN and TP inputs from runoff; C_{in} and C_{out} are the concentration of TN and TP in inlet sites and outlet sites in Dianshan Lake, respectively.

3. Results

3.1. Annual Variation of TN and TP

Annual variation of the concentrations of TN (2001–2015) and TP (1996–2015) in Dianshan Lake are presented based on the average concentration of 13 monitoring sites. As can be seen from Figure 2, the average concentration of TN increased from 2002 to 2007 (R^2 = 0.785, $p < 0.05$). In 2007, the average concentration of TN reached its peak of 4.53 mg/L, which far exceeded the Grade V water quality standards of China [29]. The average concentration of TN in Dianshan Lake decreased from the highest point of 4.53 mg/L in 2007 to a minimum of 2.85 mg/L in 2015, which indicates that eutrophication in Dianshan has been reduced to some extent (R^2 = 0.737, $p < 0.05$). However, the water quality was still less than the grade II or III water quality standards of China. Compared with interannual variability of the average concentration of TN, interannual variability of TP means the concentration in Dianshan Lake shows a trend of ups and downs during 1996–2015, but the highest value of 0.24 mg/L still appeared in 2007. TP average concentration in Dianshan Lake fluctuated, showing an obvious increasing trend before 2007 (R^2 = 0.673, $p < 0.05$), and then proceeding downward after 2007 (R^2 = 0.345, $p < 0.1$).

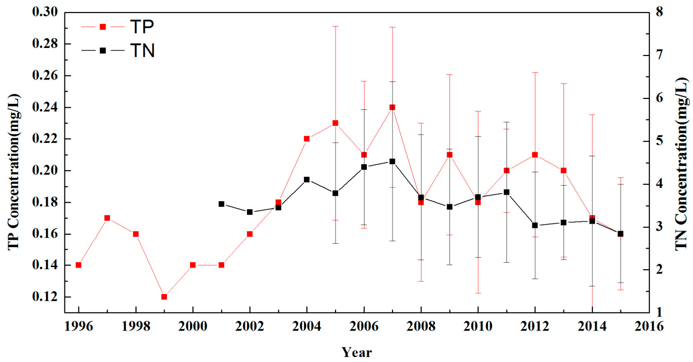

Figure 2. Interannual variations of total nitrogen (TN) and total phosphorous (TP) in Dianshan Lake from 1996 to 2015 (error bars represent the seasonal variation of the TN and TP concentrations at 13 sites in Dianshan lake).

3.2. Seasonal Variation of TN and TP

We divided TN and TP concentrations in Dianshan Lake into four categories during the study period (2005–2015) based on seasonal differences. As can be seen from Table 1, the distribution of TN in Dianshan Lake showed an obvious seasonal difference. TN concentrations had significantly seasonal variation ($p < 0.01$), except for between spring and winter ($p > 0.05$). The average mass concentration of TN in Dianshan Lake in winter (December, January, and February) and spring (March, April, and May) were significantly higher than that in summer (June, July, and August) and autumn (September, October, and November). The highest average concentration of TN occurred in winter (4.62 mg/L) and spring (4.66 mg/L)—especially in February and March, with the average concentrations of 8.08 mg/L and 7.84 mg/L, respectively. Compared with the average mass concentration of TN in Dianshan Lake in winter and spring, the value of TN concentration in summer and autumn was small with average concentrations of 2.68 mg/L and 2.37 mg/L, respectively. With an increase in precipitation and river runoff, the average concentration of TN in Dianshan Lake showed a downward trend from spring to summer, while the average concentration of TN in Dianshan Lake increased from autumn to winter, with less precipitation and river runoff [3].

Different from the seasonal variation of TN, the seasonal variation of TP in Dianshan Lake displayed a small variation (Table 2). TP concentrations were not significantly different between seasons ($p > 0.05$), except spring and summer, and spring and winter. The average concentrations of TP in Dianshan Lake were higher in summer, autumn, and winter (0.207, 0.199, and 0.197 mg/L, respectively), while being lower in spring (0.186 mg/L).

3.3. Spatial Distribution of TN and TP

The spatial distribution of TN and TP in the four seasons in Dianshan Lake were analyzed from 2005 to 2015. There was a similar feature of spatial distribution of TN and TP in Dianshan Lake during the study period. For TN (Figure 3), the northern area showed the highest value, and gradually decreased from north to south. The southwestern area is the secondary center of the highest value. The average concentration of TN in Dianshan Lake exhibits a characteristic decrease from north to south, and west to east. The distribution of TN in the four seasons showed a unique feature with two high concentrations centered on Dianshan Lake. Additionally, the highest TN values were mainly distributed in the inlet monitoring sites (S1–S4); for example, among 13 sites, S1 showed the highest value, and the lowest TN values were distributed in the outlet monitoring sites (S12–S13). As can be seen from Figure 4, the spatial distribution of TP showed similar features as TN. The northern area showed the highest TP value, and gradually decreased from north to south in all seasons. The highest TP values were mainly distributed in the inlet monitoring sites, while the lowest TP values were distributed in the outlet monitoring sites.

Table 1. Seasonal variation of TN in Dianshan Lake from 2005 to 2015 (units: mg/L).

Sites	No.	Spring			Summer			Autumn			Winter		
		March	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**	**January**	**February**
IS	**S1**	**7.84** ± 1.76	**6.75** ± 2.62	**6.57** ± 2.72	**5.35** ± 2.15	**4.72** ± 2.31	**2.48** ± 1.29	**2.90** ± 1.47	**2.89** ± 0.77	**4.25** ± 1.73	**5.44** ± 1.58	**7.29** ± 1.11	**8.08** ± 2.51
	S2	4.44 ± 0.86	4.03 ± 0.69	2.98 ± 0.65	2.68 ± 0.7	2.21 ± 0.4	1.87 ± 0.53	2.00 ± 0.8	2.07 ± 0.38	2.48 ± 0.44	2.95 ± 0.88	4.09 ± 0.82	4.23 ± 0.77
	S3	5.85 ± 1.15	5.22 ± 1.4	4.53 ± 1.39	4.35 ± 0.84	3.91 ± 0.86	2.86 ± 0.57	2.82 ± 0.5	3.19 ± 0.67	4.01 ± 0.73	4.47 ± 1.46	5.35 ± 1.2	5.47 ± 1.1
	S4	**4.50** ± 1.36	3.90 ± 0.79	3.45 ± 1.18	2.81 ± 0.8	2.21 ± 0.64	2.23 ± 0.86	1.98 ± 0.46	2.28 ± 0.65	2.59 ± 0.47	3.25 ± 0.79	**3.79** ± 0.65	**4.09** ± 1.13
CLS	**S5**	6.75 ± 0.76	6.12 ± 1.9	5.30 ± 2.02	4.86 ± 1.94	3.88 ± 1.72	1.92 ± 0.73	2.50 ± 1.22	2.16 ± 0.83	3.49 ± 0.91	4.93 ± 1.68	6.22 ± 0.88	7.27 ± 1.38
	S6	5.37 ± 1.03	4.96 ± 1.66	3.74 ± 1.27	3.62 ± 1.4	2.51 ± 0.89	1.87 ± 0.54	2.12 ± 0.89	2.05 ± 0.56	2.72 ± 0.9	3.79 ± 1.56	5.40 ± 1.59	5.43 ± 1.72
	S7	5.51 ± 1.03	5.30 ± 1.87	4.27 ± 1.59	3.52 ± 0.93	3.38 ± 0.71	2.35 ± 0.58	2.24 ± 0.53	2.60 ± 0.62	3.53 ± 0.68	3.82 ± 0.89	4.30 ± 1.58	5.14 ± 0.99
	S8	4.56 ± 1.24	4.34 ± 0.94	3.11 ± 1.26	2.73 ± 0.82	2.41 ± 0.98	1.74 ± 0.5	2.08 ± 0.6	2.31 ± 0.55	2.63 ± 0.45	3.26 ± 1.03	4.02 ± 0.95	4.58 ± 0.96
	S9	5.49 ± 1.02	4.12 ± 1.01	2.71 ± 0.99	**2.26** ± 1.02	**1.96** ± 0.65	1.72 ± 0.53	1.54 ± 0.46	**1.73** ± 0.45	**1.93** ± 0.56	3.16 ± 1.23	4.52 ± 1.13	5.42 ± 1.76
	S10	5.06 ± 1.2	4.02 ± 0.82	3.06 ± 0.99	2.55 ± 0.64	2.12 ± 0.52	1.82 ± 0.27	1.59 ± 0.39	1.80 ± 0.38	2.01 ± 0.4	3.26 ± 1.04	4.37 ± 1.79	5.21 ± 1.33
	S11	4.76 ± 1.13	**3.64** ± 0.58	3.46 ± 1.43	2.90 ± 0.73	2.20 ± 0.73	1.82 ± 0.53	1.97 ± 0.58	2.23 ± 0.62	2.81 ± 0.37	3.33 ± 0.79	4.14 ± 1.62	4.75 ± 1.18
OS	**S12**	5.56 ± 1.19	4.39 ± 1.13	2.94 ± 1.08	2.33 ± 0.61	2.27 ± 0.81	1.80 ± 0.61	**1.33** ± 0.41	1.78 ± 0.44	1.94 ± 0.62	**2.88** ± 1.03	4.31 ± 1.93	5.27 ± 1.27
	S13	5.50 ± 1.3	4.54 ± 0.98	**2.93** ± 1.18	2.46 ± 0.75	2.11 ± 0.53	**1.68** ± 0.33	1.54 ± 0.45	1.89 ± 0.54	2.42 ± 0.96	2.99 ± 1.14	4.76 ± 1.07	5.04 ± 1.36

Note: the bolded numbers mean the maximum and minimum of TN concentration in each column. IS: inlet sites; CLS: central lake sites; OS: outlet sites.

Table 2. Seasonal variation of TP in Dianshan Lake from 2005 to 2015 (units: mg/L).

Sites	No.	Spring			Summer			Autumn			Winter		
		March	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**	**January**	**February**
IS	**S1**	**0.36** ± 0.07	**0.34** ± 0.13	**0.33** ± 0.16	**0.33** ± 0.1	**0.36** ± 0.14	**0.30** ± 0.06	**0.34** ± 0.11	**0.20** ± 0.09	**0.23** ± 0.1	**0.27** ± 0.07	**0.32** ± 0.1	**0.38** ± 0.16
	S2	0.21 ± 0.05	0.17 ± 0.05	0.15 ± 0.03	0.19 ± 0.05	0.23 ± 0.06	0.22 ± 0.04	0.23 ± 0.06	0.17 ± 0.07	0.19 ± 0.05	0.16 ± 0.04	0.19 ± 0.06	0.19 ± 0.07
	S3	0.25 ± 0.13	0.21 ± 0.14	0.21 ± 0.09	0.22 ± 0.1	0.23 ± 0.09	0.22 ± 0.08	**0.21** ± 0.06	0.17 ± 0.06	0.21 ± 0.05	0.22 ± 0.11	0.25 ± 0.11	0.23 ± 0.13
	S4	0.16 ± 0.07	0.16 ± 0.08	0.14 ± 0.1	0.17 ± 0.08	0.18 ± 0.08	**0.17** ± 0.05	**0.21** ± 0.07	0.15 ± 0.05	**0.16** ± 0.07	0.15 ± 0.1	**0.13** ± 0.05	**0.14** ± 0.07
CLS	**S5**	0.32 ± 0.07	0.26 ± 0.08	0.25 ± 0.09	0.27 ± 0.11	0.31 ± 0.1	0.28 ± 0.09	0.32 ± 0.1	0.18 ± 0.07	0.19 ± 0.05	0.23 ± 0.08	0.29 ± 0.05	0.34 ± 0.1
	S6	0.22 ± 0.08	0.19 ± 0.07	0.16 ± 0.04	0.21 ± 0.06	0.25 ± 0.09	0.29 ± 0.1	0.27 ± 0.09	0.17 ± 0.05	0.17 ± 0.05	0.18 ± 0.06	0.23 ± 0.08	0.24 ± 0.09
	S7	0.21 ± 0.11	0.19 ± 0.1	0.16 ± 0.07	0.18 ± 0.06	0.22 ± 0.08	0.23 ± 0.07	0.22 ± 0.06	0.17 ± 0.06	0.19 ± 0.07	0.17 ± 0.06	0.15 ± 0.08	0.21 ± 0.15
	S8	**0.15** ± 0.08	0.15 ± 0.06	0.11 ± 0.1	0.14 ± 0.06	**0.16** ± 0.05	0.20 ± 0.04	0.22 ± 0.07	0.15 ± 0.04	0.17 ± 0.05	0.15 ± 0.06	0.15 ± 0.06	0.17 ± 0.09
	S9	0.18 ± 0.09	**0.13** ± 0.04	0.11 ± 0.03	**0.11** ± 0.04	0.18 ± 0.06	0.21 ± 0.05	0.26 ± 0.12	0.16 ± 0.03	0.17 ± 0.05	**0.14** ± 0.06	0.17 ± 0.06	0.21 ± 0.08
	S10	0.19 ± 0.05	**0.13** ± 0.03	0.12 ± 0.03	0.14 ± 0.03	0.17 ± 0.03	0.19 ± 0.05	0.26 ± 0.11	0.15 ± 0.04	**0.16** ± 0.04	0.16 ± 0.09	0.17 ± 0.08	0.18 ± 0.07
	S11	0.16 ± 0.09	**0.13** ± 0.07	0.12 ± 0.06	0.16 ± 0.07	**0.16** ± 0.05	0.18 ± 0.05	**0.21** ± 0.06	**0.14** ± 0.04	0.17 ± 0.05	0.17 ± 0.07	0.16 ± 0.08	0.19 ± 0.1
OS	**S12**	0.21 ± 0.06	0.14 ± 0.04	**0.10** ± 0.02	0.15 ± 0.09	0.17 ± 0.04	0.19 ± 0.05	0.25 ± 0.09	0.16 ± 0.04	0.18 ± 0.06	0.15 ± 0.06	0.16 ± 0.09	0.19 ± 0.08
	S13	0.22 ± 0.07	0.15 ± 0.04	0.11 ± 0.03	0.13 ± 0.04	0.18 ± 0.05	0.21 ± 0.04	0.26 ± 0.09	0.17 ± 0.03	0.18 ± 0.05	**0.14** ± 0.05	0.16 ± 0.05	0.20 ± 0.09

Note: the bolded numbers mean the maximum and minimum of TP concentration in each column.

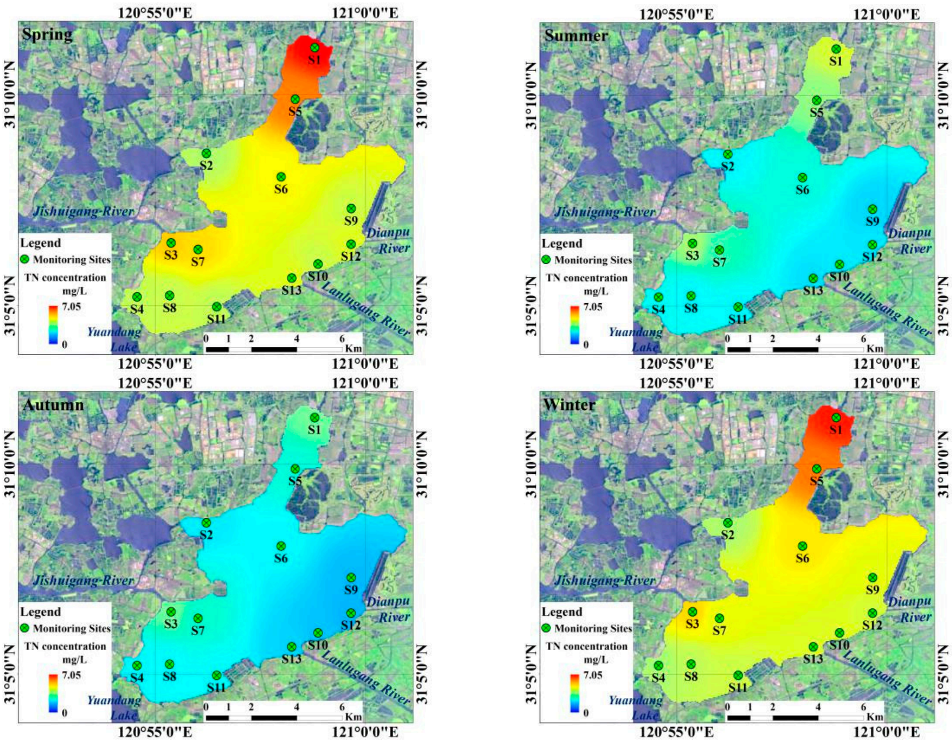

Figure 3. Spatial distribution of TN in Dianshan Lake from 2005 to 2015.

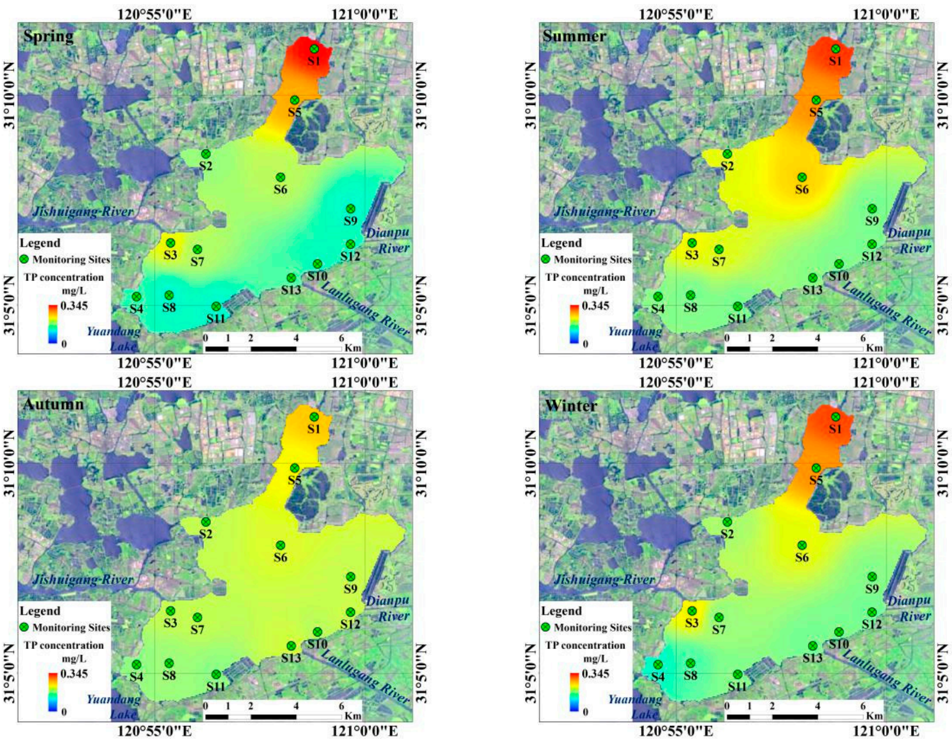

Figure 4. Spatial distribution of TP in Dianshan Lake from 2005 to 2015.

Overall, the spatial distribution of TN and TP in Dianshan Lake were similar, showing a characteristic decrease from north to south. The highest TN and TP values were mainly distributed in the inlet monitoring sites, while the lowest values were distributed in the outlet monitoring sites. However, the spatial distribution of TP was slightly different from TN; for example, the northern area showed the highest TP concentration in spring, summer, and winter, while the northern area recorded the highest TN concentration in spring and winter.

3.4. Water Self-Purification Ability

Water volumes of inflow and outflow in Dianshan Lake were about 17.863 $\times$ 10^8 m^3 and 17.56 $\times$ 10^8 m^3, respectively [30]. According to previous research, we obtained the dry and wet deposition of TN and TP in Dianshan Lake as about 389.78 t/yr and 4.83 t/yr, respectively; TN and TP inputs from runoff are about 109.79 t/yr and 8.93 t/yr, respectively [31]. Therefore, we can calculate that TN is entering and leaving the lake are about 7096.97 t/yr and 4807 t/yr, respectively and TP is entering and leaving the lake are about 371.86 t/yr and 259.7 t/yr, respectively. So, the self-purification levels of TN and TP in Dianshan Lake are about 2289.97 t/yr and 112.16 t/yr.

4. Discussion

4.1. Analyses of the Spatio-Temporal Distribution of TN and TP

Ecosystem recovery work in Dianshan Lake was carried out, and the authorities in Shanghai have strengthened the management of nutrients and water quality in Dianshan Lake; for example, during the second round of environmental protection (2003–2005), the government removed the caged fish in Dianshan Lake since 2004 [32]. However, the average concentration of TN and TP in Dianshan Lake in a given period were still rising, perhaps because the recovery of water bodies needs some time. In 2001–2007 (especially in 2007), the average concentration of TN and TP in Dianshan Lake reached a peak, while the average concentration of TN showed a downward trend after 2007, with the continued improvement of the ecological environment. This result suggests that even if the ecological restoration and management are done, pollutants are controlled, and emissions of nutrients are reduced, the concentration of TP and TN in the water will not fall immediately, will continue to rise for a period until the concentration of TN and TP in the water are controlled, and will then fall to a certain level. A similar phenomenon was observed by Cheng et al. (2012) [32] in the surface water of Dianshan Lake, and by Yang et al. (2013) [17] in Chaohu Lake, which was highly eutrophic and water quality showed no substantial improvement during 2001 to 2011 after the restoration of Chaohu Lake.

The area we studied is defined as a drinking water resource conservation area; industrial development is limited, with the breeding of livestock and poultry being forbidden. According to previous studies, agriculture dominates the pollution sources deteriorating the water quality in the area [3,27,33]. Dianshan Lake watershed is in the subtropical humid monsoon climate; rainfall and runoff change seasonally, so the concentration of TN and TP in Dianshan Lake showed seasonal variations. During the monsoon season and autumn, the precipitation increased and concentrated; as a result, runoff increased at the same time, which diluted the TN and TP concentrations (dilution effect). Previous studies also showed that TN and TP concentrations in shallow water showed highly seasonal variations [6,17,34,35]. TN and TP concentrations in winter and spring were significantly higher than that in summer and autumn. The average concentration of TN declined from spring to autumn, and TP decreased from summer to autumn with the increase in precipitation and river runoff, while the average concentration of TN and TP increased from autumn to winter with reduced precipitation and river runoff.

The spatial distribution of TN and TP at different monitoring sites were totally different, showing a characteristic which gradually decreased from north to south. This is because of Kunshan City, located to the north of Dianshan Lake, where industrial and agricultural waste water and anthropogenic sewage were released and entered into the northern waters of Dianshan Lake through inlet S1, which accelerated water pollution and nutrient enrichment in northern waters.

In the southwest, a shipping channel is a primary function on the water, and along with human activities, a large amount of transport emissions were released into the water through inlet S3, resulting in a relatively higher average concentration of TN and TP in Dianshan Lake. Due to the absorption and purification of aquatic plants, N and P release were significantly reduced, and inlet S4 showed the lowest TN and TP values. Moreover, the fresh water from Yuandang Lake flowed into Dianshan Lake, diluting the concentration of nitrogen and phosphorous in inlet S4 to some extent.

Located in the exchange zone between Dianshan Lake and Huangpu River, eastern waters (especially those outlet sites) were surrounded by numerous tidal rivers and showed relatively lower TN and TP concentrations. These rivers connected Dianshan Lake and Huangpu River, and their water levels changed regularly, which updated the water quality constantly in Dianshan Lake and caused nutrients in the water to diffuse and dilute.

4.2. Water Self-Purification Ability Estimation

Dianshan Lake is downstream of the Taihu Lake Zone, so its water and river runoff were from Taihu Lake and other upstream rivers. Changes in the water levels of Dianshan Lake are controlled by inputs and outputs compared to the total volume of the lake. The dominant input sources of Dianshan Lake are runoff carried by streams and channels from the lake's catchment area. Significant output sources are surface and groundwater flows.

We calculate that self-purification of TN and TP in Dianshan Lake are about 2289.97 t/yr and 112.16 t/yr. The results are close to the findings given by Lu et al. [31], who estimated that self-purification of TN and TP in Dianshan Lake were about 1965 t/yr and 118 t/yr, respectively, in 2011. The self-purification capacity of Dianshan Lake reflects its ability to absorb pollutants. The background concentration of nitrogen and phosphorus pollutants in the water (which determines the nutritional status) has a greater direct impact on its purification potential. The 20-year average concentrations of TN and TP in Dianshan were about 3.60 mg/L and 0.18 mg/L, respectively, which revealed that Dianshan Lake faces moderate eutrophication.

5. Conclusions

In this paper, we used long-term monitoring data of TN and TP in Dianshan Lake from 1996 to 2015 and found that the interannual variability of the average concentration of TN in Dianshan Lake changed greatly, showing a characteristic increase before a decline. The average concentration of TN in Dianshan Lake showed an obvious downward trend, especially after 2007. Interannual variability of the average concentration of TP in Dianshan Lake fluctuated violently, and the average concentration of TP showed a downward trend after 2007 due to ecosystem recovery work.

The seasonal variations of TN and TP in Dianshan Lake were similar. Higher TN concentration occurred in winter and spring, while higher TP concentration appeared in summer, autumn, and winter. Precipitation and river runoff have an impact on seasonal variations of TN and TP in Dianshan Lake, with higher TN values in winter and spring and higher TP values in spring and summer.

The spatial distribution of TN and TP in Dianshan Lake were similar, showing a characteristic of concentration which decreased from north to south and west to east. The northern area showed the highest value, and decreased from north to south gradually in all seasons. The highest TN and TP values were mainly distributed in those inlet monitoring sites, while the lowest TP values were distributed in those outlet monitoring sites.

Based on long-term hydrological observations and data from 13 monitoring sites in Dianshan Lake, we calculated that the self-purification capacity of nitrogen and phosphorus of Dianshan Lake were about 2289.97 t/yr and 112.16 t/yr, respectively. Our study showed that Dianshan Lake was highly eutrophic, and its water quality showed a substantial improvement from 1996 to 2015.

Acknowledgments: This work was jointly supported by the National Natural Science Foundation of China (Grant No. 41671467, No. 41473049, and No. 41301221), the Ministry of Science and Technology Project Foundation (2014FY210600), the Shanghai Municipal Natural Science Foundation (Grant No. ZR1412100), and the research fund of the SKLEC (2015KYYW03).

Author Contributions: D.W. and G.X. conceived and designed the experiments; G.X. and G.W. performed the research; D.W., G.W. and W.Y. analyzed the data; G.X. and G.W. wrote the paper; D.W. finalized the manuscript discussing with Y.C., and Z.C.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Chen, X.H.; Li, X.P. Using quantile regression to analyze the stressor-response relationships between nutrient levels and algal biomass in three shallow lakes of the Lake Taihu Basin, China. *Chin. Sci. Bull.* **2014**, *59*, 3621–3629. [CrossRef]
2. An, S.; Wang, L. *Wetland Restoration: Shanghai Dalian Lake Project*; Springer Environmental Science and Engineering; Science Press: Beijing, China; Springer: Berlin/Heidelberg, Germany, 2014.
3. Wang, S.B.; Ma, X.X.; Fan, Z.Q.; Zhang, W.Q.; Qian, X.Y. Impact of nutrient losses from agricultural lands on nutrient stocks in Dianshan Lake in Shanghai, China. *Water Sci. Eng.* **2014**, *7*, 373–383.
4. Schiewer, U.; Schernewski, G. Self-purification capacity and management of Baltic coastal ecosystems. *J. Coast. Conserv.* **2004**, *10*, 25–32. [CrossRef]
5. Strokal, M.; Kroeze, C. Nitrogen and phosphorus inputs to the Black Sea in 1970–2050. *Reg. Environ. Chang.* **2013**, *13*, 179–192. [CrossRef]
6. Zhao, Z.H.; Mi, T.F.; Xia, L.L.; Yan, W.M.; Jiang, Y.; Gao, Y.Z. Understanding the patterns and mechanisms of urban water ecosystem degradation: Phytoplankton community structure and water quality in the Qinhuai River, Nanjing City, China. *Environ. Sci. Pollut. Res.* **2013**, *20*, 5003–5012. [CrossRef] [PubMed]
7. González, S.O.; Almeida, C.A.; Calderón, M.; Mallea, M.A.; González, P. Assessment of the water self-purification capacity on a river affected by organic pollution: Application of chemometrics in spatial and temporal variations. *Environ. Sci. Pollut. Res.* **2014**, *21*, 10583–10593. [CrossRef] [PubMed]
8. Blaas, H.; Kroeze, C. Possible future effects of large-scale algae cultivation for biofuels on coastal eutrophication in Europe. *Sci. Total Environ.* **2014**, *496*, 45–51. [CrossRef] [PubMed]
9. Blaas, H.; Kroeze, C. Excessive nitrogen and phosphorus in European rivers: 2000–2050. *Ecol. Indic.* **2016**, *67*, 328–337. [CrossRef]
10. Sun, L.Q.; Wang, Z.Y.; Wei, X.; Li, P.; Zhang, H.M.; Li, M.; Li, B.A.; Wang, S.C. Enhanced biological nitrogen and phosphorus removal using sequencing batch membrane-aerated biofilm reactor. *Chem. Eng. Sci.* **2015**, *135*, 559–565. [CrossRef]
11. Kim, G.Y.; Yun, Y.M.; Shin, H.S.; Kim, H.S.; Han, J.I. Scenedesmus-based treatment of nitrogen and phosphorus from effluent of anaerobic digester and bio-oil production. *Bioresour. Technol.* **2015**, *196*, 235–240. [CrossRef] [PubMed]
12. Qin, B.Q.; Gao, G.; Zhu, G.W. Lake eutrophication and its ecosystem response. *Chin. Sci. Bull.* **2013**, *58*, 961–970. [CrossRef]
13. Han, T.; Zhang, H.J.; Hu, W.P.; Deng, J.C.; Li, Q.Q.; Zhu, G.E. Research on self-purification capacity of Lake Taihu. *Environ. Sci. Pollut. Res.* **2015**, *22*, 8201–8215. [CrossRef] [PubMed]
14. Wei, G.L.; Yang, Z.F.; Cui, B.S.; Li, B.; Chen, H.; Bai, J.H.; Dong, S.K. Impact of Dam Construction on Water Quality and Water Self-Purification Capacity of the Lancang River, China. *Water Resour. Manag.* **2009**, *23*, 1763–1780. [CrossRef]
15. Ostroumov, S.A. Biocontrol of water quality: Multifunctional role of biota in water self-purification. *Russ. J. Gen. Chem.* **2011**, *80*, 2754–2761. [CrossRef]
16. Cukrov, N.; Cmuk, P.; Mlakar, M.; Omanović, D. Spatial distribution of trace metals in the Krka River, Croatia: An example of the self-purification. *Chemosphere* **2008**, *72*, 1559–1566. [CrossRef] [PubMed]
17. Yang, L.B.; Lei, K.; Meng, W.; Fu, G.; Yan, W.J. Temporal and spatial changes in nutrients and chlorophyll-a in a shallow lake, Lake Chaohu, China: An 11-year investigation. *J. Environ. Sci.* **2013**, *25*, 1117–1123. [CrossRef]
18. Cai, L.L.; Zhu, G.W.; Zhu, M.Y.; Xu, H.; Qin, B.Q. Effects of temperature and nutrients on phytoplankton biomass during bloom seasons in Taihu Lake. *Water Sci. Eng.* **2012**, *5*, 361–374.
19. Paerl, H.W.; Xu, H.; McCarthy, M.J.; Zhu, G.W.; Qin, B.Q.; Li, Y.Q.; Gardner, W.S. Controlling harmful cyanobacterial blooms in a hyper-eutrophic lake (Lake Taihu, China): The need for a dual nutrient (N & P) management strategy. *Water Res.* **2011**, *45*, 1973–1983. [PubMed]

20. Wang, C.; Bi, J.; Ambrose, R.B. Development and application of mathematical models to support total maximum daily load for the Taihu Lake's influent rivers, China. *Ecolog. Eng.* **2015**, *83*, 258–267. [CrossRef]
21. National Development and Reform Commission. *National Development and Reform Commission: The Overall Program on Integrated Regulation of Taihu Lake Basin*; National Development and Reform Commission: Beijing, China, 2013. (In Chinese)
22. Yang, B.; Jiang, Y.J.; He, W.; Liu, W.X.; Kong, X.Z.; Jørgensen, S.E.; Xu, F.L. The tempo-spatial variations of phytoplankton diversities and their correlation with trophic state levels in a large eutrophic Chinese lake. *Ecol. Indic.* **2016**, *66*, 153–162. [CrossRef]
23. Cheng, X.; Li, X.P. Long-Term Changes in Nutrients and Phytoplankton Response in Lake Dianshan, a Shallow Temperate lake in China. *J. Freshw. Ecol.* **2010**, *25*, 549–554. [CrossRef]
24. Eggert, A.; Schneider, B. A nitrogen source in spring in the surface mixed-layer of the Baltic Sea: Evidence from total nitrogen and total phosphorus data. *J. Mar. Syst.* **2015**, *148*, 39–47. [CrossRef]
25. Wang, J.; Yuan, Q.; Xie, B. Temporal dynamics of cyanobacterial community structure in Dianshan Lake of Shanghai, China. *Ann. Microbiol.* **2015**, *65*, 105–113. [CrossRef]
26. Lin, W.Q.; Lu, S.Q.; Chen, Y.Z. An application of Eco-Dynamic model in evaluting Eutrophication control measures for Dianshan Lake in Shanghai. *Shanghai Environ. Sci.* **2010**, *29*, 1–10. (In Chinese).
27. Liu, F.X.; Song, X.F.; Zou, G.Y.; Fu, Z.S.; Liu, Y.Q.; Xue, L.H.; Yang, L.Z. Reduce-retain-reuse-restore technology for the controlling the agricultural non-point source pollution in countryside in China: Eco-restoration technology. *J. Agro-Environ. Sci.* **2013**, *32*, 2105–2111. (In Chinese).
28. ESRI. ArcGIS for Desktop. Available online: http://desktop.arcgis.com/en/arcmap/10.3/tools/3d-analyst-toolbox/how-idw-works.htm (accessed on 10 February 2017).
29. Environmental Quality Standards for Surface Water in China (GB3838-2002). Available online: http://kjs.mep.gov.cn/hjbhbz/bzwb/shjbh/shjzlbz/200206/t20020601_66497.htm (accessed on 1 June 2002).
30. Zhang, J.Y.; Zhang, S.N. Preliminary study on water resources of Dianshan Lake. *J. Lake Sci.* **1992**, *4*, 65–70. (In Chinese).
31. Lu, J.; Li, X.P.; Cheng, X.H. Analysis of Water Pollution in Dianshan Lake. *Environ. Sci. Manag.* **2011**, *36*, 116–120. (In Chinese).
32. Cheng, X.; Li, X.P.; Chen, X.H. Statistical characteristics of eutrophication process in Dianshan Lake. *Acta Ecol. Sin.* **2012**, *32*, 1355–1362. (In Chinese). [CrossRef]
33. Chen, H.; Han, Q.; Zhou, H.W. Water pollution analysis and integrated control countermeasures for Dianshan Lake. *Water Resour. Prot.* **2011**, *27*, 36–40. (In Chinese).
34. Yoshioka, K.; Kamiya, H.; Kano, Y.; Saki, Y.; Yamamuro, M.; Ishitobi, Y. The relationship between seasonal variations of total-nitrogen and total-phosphorus in rainfall and air mass advection paths in Matsue, Japan. *Atmos. Environ.* **2009**, *43*, 3496–3501. [CrossRef]
35. Krzyk, M.; Drev, D.; Kolbl, S.; Panjan, J. Self-purification processes of Lake Cerknica as a combination of wetland and SBR reactor. *Environ. Sci. Pollut. Res.* **2015**, *22*, 20177–20185. [CrossRef] [PubMed]