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# Spatial–Temporal Variations of Total Nitrogen and Phosphorus in Poyang, Dongting and Taihu Lakes from Landsat-8 Data

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**Abstract:** Poyang Lake, Dongting Lake, and Taihu Lake are the largest freshwater lakes in the middle and lower reaches of the Yangtze River, China. In recent years, the eutrophication level of lakes has increased with the development of the social economy and caused many environmental and social problems. The concentrations of total nitrogen (TN) and total phosphorus (TP) are the key indicators of the degree of eutrophication, but the traditional ground monitoring methods are not capable of capturing such parameters in whole lakes with high spatial-temporal resolution. In this paper, empirical models are established and evaluated between the TN and TP and remote sensing spectral factors in the three lakes using Landsat 8 Operational Land Imager (OLI) satellite data and in-situ data. The results show that the inversion accuracy is higher than 75%. The TN and TP concentrations in the three lakes are inversed based on the Google Earth Engine (GEE) platform from 2014 to 2020 and their spatial-temporal variations are analyzed. The results show that the concentrations of TN and TP in Poyang Lake were decreased by 5.99% and 7.13% over 7 years, respectively, and the TN in Dongting Lake was decreased by 5.25% while the TP remained stable. The temporal changes in TN and TP concentrations displayed seasonal variations. A low concentration was observed in summer and high concentrations were in spring and winter. The average concentrations of TN and TP in Taihu Lake were higher than that of the other two lakes. The TP concentration was increased by 17.3% over 7 years, while the TN concentration remained almost stable. The variation in TN in Taihu Lake was the same as the growth cycle of algae, with higher value in spring and winter and lower value in summer, while the concentration of TP was lower in spring and winter and higher in summer. The spatial distribution of TN and TP concentrations in the three major lakes was significantly affected by human activities, and the concentrations of TN and TP were higher in areas near cities and agricultural activities.

**Keywords:** Poyang Lake; Dongting Lake; Taihu Lake; Landsat 8; total nitrogen; total phosphorus



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## 1. Introduction

More than 2800 lakes are in China, with an area larger than 1 km$^2$. The middle and lower reaches of the Yangtze River have the largest freshwater lakes in China with many bigger cities. It is a substantial agricultural and industrial base in China and one of the most economically developed regions in the country. A large amount of industrial wastewater and urban domestic sewage were produced during the economic development of the plains in the middle and lower reaches of the Yangtze River, but the sewage and wastewater treatment measures were not perfect. In addition, the excessive use of chemical fertilizers in agriculture also increased the pollution of the lakes. Since the beginning of the last century, due to the rapid development of the economy and human activities, many lakes worldwide have experienced eutrophication. Eutrophication is a form of organic pollution, mainly caused by the discharge of industrial wastewater, domestic sewage, and the use of fertilizers and pesticides. It increases the water nutrients such as TN and TP and promotes the growth of algae in the water. Algae death consumes dissolved oxygen in the water, and some algae produce toxic substances when they decompose. The decomposed remains of the algae release nitrogen and phosphorus substances to continue this cycle and create a bloom in the lake [1,2]. This will lead to the death of other aquatic organisms and destroy the ecological balance of the water environment [3].

The progress of industry and agriculture coupled with the impact of climate change aggravates the eutrophication of lakes, which threatens the stability of the lake ecosystem and restricts the sustainable development of the social economy of the cities around the lake. Dongting Lake, Poyang Lake, and Taihu Lake are the three largest freshwater lakes in the middle and lower reaches of the Yangtze River. Although the eutrophication in these lakes has been controlled well recently, the governance situation is still difficult. Monitoring the water quality of lakes is the key component, providing data to analyze the temporal and spatial changes and solve the problem of eutrophication of lakes. It will also permit exploration of the reasons for eutrophication in lakes and help to restore the water ecology and water environment in the middle and lower reaches of the Yangtze River [4]. Total nitrogen (TN) and total phosphorus (TP) are the two most important indices in the eutrophication of water bodies. The traditional monitoring method of TN and TP is the chemical sampling method. This method consumes a lot of time and effort and also represents nearby water quality by sampling points. It cannot obtain data on the water quality parameters for whole lakes with long-term continuous monitoring. Remote sensing technology can conduct large-area, low-cost, and real-time tracking, representing the new technique of lake water quality monitoring [5].

As early as the 1970s, scientists began to explore remote sensing satellites to retrieve water quality parameters. Kstrand et al. (1992) established a regression model of water quality data along the east coast of Sweden based on Landsat TM images [6]. Wang et al. (2000) constructed models of seven water quality parameters in Taihu Lake based on Landsat TM images [7]. Gao et al. (2014) proved the potential of band combination and a regional multivariate statistical algorithm to estimate TP concentrations in large lakes based on HJ-1A CCD images [8]. Lim et al. (2015) constructed a water quality estimation model of the suspended solids (SS), TN, TP, and Chl-a in Nadong River based on Landsat 8 OLI images and showed a good correlation of these water quality parameters with Landsat 8 images [9]. Standard methods include semi-analytical and empirical methods. The semi-analytical method requires a hyperspectral imager to measure high-spectral-resolution data in the field, which selects the appropriate band or band combination according to the spectral characteristics of the water quality parameters and establishes an inversion model of remote sensing data and water quality parameters in a suitable way. The empirical method only measures in-situ water quality parameters, analyzes the correlation between the measured data and the corresponding remote sensing band value, establishes a regression model with selection of the optimal band, and then estimates water quality parameters [10,11].

Past research was mainly limited by the resolution of remote sensing satellites with poor accuracy. Moreover, the available bands of satellites are relatively fewer, which restricts the construction of high-accuracy inversion models. Furthermore, the downloading and processing flow of remote sensing images are cumbersome, so it is difficult to carry out a large-scale and long-term inversion of water quality parameters. In this paper, remote sensing images are processed based on the Google Earth Engine (GEE) platform from the high-resolution remote sensing satellite Landsat 8, and the TN and TP concentrations of the three major freshwater lakes in the middle and lower reaches of the Yangtze River are evaluated from 2014 to 2020 using empirical methods. Then, the temporal and spatial changes in water quality parameters in the three lakes are analyzed and the related factors of the TN and TP variations are discussed.

## 2. Study Area and Data

### 2.1. Study Area

Poyang Lake is located in the northern part of Jiangxi Province and is the largest freshwater lake in China. The lake area ranges from 500 km$^2$ at a low water level (12 m) to a maximum of 4125 km$^2$ at a high-water level (20 m). The northern lake area is connected to the Yangtze River with a long and narrow river, and the southern lake is the main area. Poyang Lake is a seasonal lake with a considerable water level drop between the year and the season, up to 16 m per year. It plays a major role in regulating the water level of rivers, conserving water sources, improving the local climate, and maintaining the ecological balance of the surrounding areas. The eutrophication index of Poyang Lake increased from 40 in 1988 to 52 in 2008 [12]. The Three Gorges Project, as the largest hydroelectric station in the world, was began in 2003 and completed in 2009. It has weakened the self-purification capacity of Poyang Lake and caused the water quality to further deteriorate [13]. The eutrophication of the lake has been controlled after strict management, but the problem of excessive TN and TP in the lake body still exists [14].

Dongting Lake is located in the middle reaches of the Yangtze River as the second-largest freshwater lake in China. The tributaries of the Yangtze River flow in from the north of the lake, the south and west are connected with various rivers, and the water finally flows into the Yangtze River from Chenglingji. It is an important regulation and storage lake in the Yangtze River Basin, with a strong flood storage capacity. Dongting Lake is a floodway-type lake with a large water flow and strong self-purification ability. However, the completion of the Three Gorges Project also weakened the lake's ability to purify pollutants. Dongting Lake is a substantial agricultural, aquaculture, and breeding base in China. The lake is affected by excessive TN and TP, which needs to be improved urgently [15].

Taihu Lake is located in the southern part of the Yangtze River Delta, and it is the third-largest freshwater lake in China and one of the most severely damaged large lakes by algae blooms. Taihu Lake is a shallow lake in the plain, with an average water depth of approximately 3 m, and has a long water change cycle and poor self-purification ability. Moreover, the discharge of industrial wastewater and domestic sewage in the surrounding area has resulted in extremely high levels of TN and TP in the lake, leading to the algal bloom disaster in Taihu Lake [12]. The locations of the three lakes are shown in Figure 1.

### 2.2. Remote Sensing Data

Landsat is a joint project of the United States Geological Survey (USGS) and the National Aeronautics and Space Administration (NASA), which has been observing the Earth since 1972, and, so far, eight satellites have been launched. Landsat 8 was successfully launched in 2013 and its revisit period is 16 days. It comprises the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). OLI collects image data from nine spectral bands, and bands 1–7 range from the visible band to the short-infrared band (NIR). Different combinations of bands can be used to monitor various features of the ground. Band 8 is the panchromatic band used to enhance resolution, and band 9 is sensitive to water vapor and used to detect clouds. The spatial resolution of band 8 is 15 m, and the spatial resolution of the other bands is 30 m. TIRS contains two thermal infrared bands, with a spatial resolution of 100 m, which can be used to study the Earth's surface temperature and study global warming. Landsat 8 has a higher spatial resolution than MODIS satellites and a higher time resolution than SPOT satellites, so it has excellent advantages in water quality remote sensing monitoring [16].

The required images were collected using the Google Earth Engine (GEE) platform. Compared with traditional image processing tools such as ENVI, GEE can quickly process large images online and in batches. GEE is an efficient tool that can perform fast calculations such as NDVI, predict crop-related yields, and monitor changes in drought conditions and global forest changes. It contains commonly used remote sensing satellite image data such as Landsat, MODIS, Sentinel, etc. The GEE reduces the time needed for downloading data and preprocessing image data and can rapidly estimate long-term series of required products at large-scale areas [17,18].

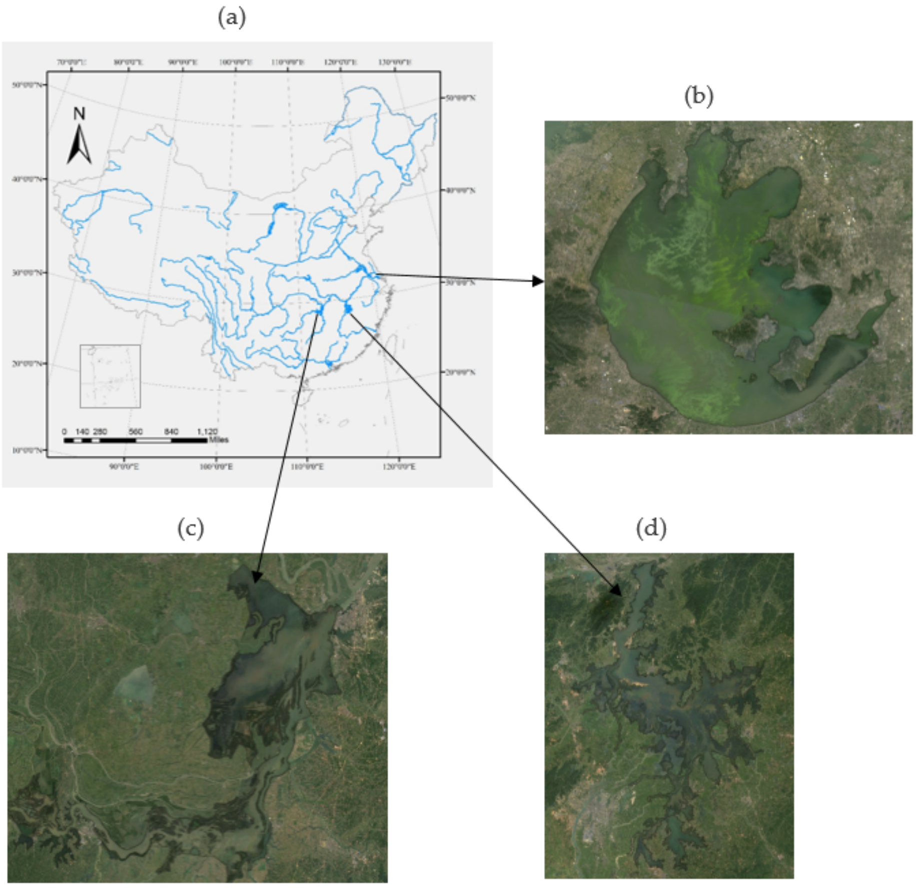



**Figure 1.** Study area with (**a**) China Water System Map (**b**) Taihu Lake (**c**) Dongting Lake and (**d**) Poyang Lake.

The Landsat 8 images used in this paper were collected from "USGS Landsat 8 Surface Reflectance Tier 1" of GEE datasets with 30 m spatial resolution. This dataset reflects the surface reflectance after atmospheric corrected and orthorectified products from the Landsat 8 OLI/TIRS sensors. Here, five visible and near-infrared (VNIR) bands and two short-wave infrared (SWIR) bands are used. The band characteristics of OLI is shown in Table 1. Landsat 8 image data of the three lakes of Poyang Lake, Dongting Lake, and Taihu Lake have been collected monthly from 2014 to 2020. The images with cloud cover over 10% were filtered out, and the remaining images included 56 scenes in Poyang Lake, 54 scenes in Dongting Lake, and 45 scenes in Taihu Lake.

**Table 1.** Characteristics of the Operational Land Imager (OLI).

| Bands | Wavelength (µm) | Resolution (m) |
|---|---|---|
| Band 1 Costal aerosol | 0.43–0.45 | 30 |
| Band 2 Blue | 0.45–0.51 | 30 |
| Band 3 Green | 0.53–0.59 | 30 |
| Band 4 Red | 0.64–0.67 | 30 |
| Band 5 Near-Infrared (NIR) | 0.85–0.88 | 30 |
| Band 6 SWIR1 | 1.57–1.65 | 30 |
| Band 7 SWIR2 | 2.11–2.29 | 30 |
| Band 8 Panchromatic | 0.50–0.68 | 15 |
| Band 9 Cirrus | 1.36–1.38 | 30 |

*2.3. Ground Data*

The in-situ data of TN and TP were collected in April 2018 and July 2018, respectively. The water samples in the three lakes were collected in two time periods and the concentrations of water quality parameters were calculated by spectrophotometry. In total, 18 groups of water samples were collected from Poyang Lake, 28 groups from Dongting Lake, and 28 groups from Taihu Lake. The TP determination method was ammonium molybdate spectrophotometry. The oxidant potassium persulfate was added to the water sample, and the phosphorus in the water sample was oxidized to orthophosphate at a temperature of 120 °C. Then, sodium hydroxide solution was added to the cooled water sample to adjust it to neutrality, and finally ascorbic acid and molybdic acid solution were added and mixed thoroughly. After the completed reaction, a blue complex was formed, and the absorbance was measured with a spectrophotometer at a 700 nm wavelength. The concentration of TP was measured by comparing experiments with blank water samples. The TN determination method was an alkaline potassium persulfate digestion ultraviolet spectrophotometric method. First, sodium hydroxide was added to the water sample to adjust it to an alkaline environment and then the alkaline potassium persulfate was added. The nitrogen in the water sample was converted into nitrate at 120 °C. Hydrochloric acid was added to adjust the water sample to acidity and measure the absorbance of the water sample at 220 nm and 275 nm in an ultraviolet spectrophotometer. The concentration of TN was measured by comparing experiments with blank water samples.

## 3. Methods and Models

Water quality remote sensing is based on the relationship between water quality parameters and remote sensing data, which is established through water surface reflectance. The water surface reflectivity R can be calculated from the water leaving radiance $L_w(\lambda)$ as [19]:

$$R = \frac{L_w(\lambda)}{E_0 \cos\theta t_d} \tag{1}$$

where $L_w(\lambda)$ is the radiance, which is obtained from the DN value received by the sensor after radiation calibration and atmospheric correction, $E_0$ is the solar irradiance at the average distance between the sun and the Earth, as measured by a satellite, $\theta$ is the zenith angle of the sun, and $t_d$ is the transmittance of the air-water interface.

According to the theory of radiation transmission, the transmission path of an electromagnetic wave in water is inferred. Many different relationships between the reflectivity and absorption coefficient $a(\lambda)$ and backscattering coefficient $b_b(\lambda)$ have been proposed for different water bodies. The most common water reflectance model was proposed by Lee [20]:

$$R = \frac{ft^2}{Q(\lambda)n^2} \frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)} \approx K \frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)} \tag{2}$$

where $f$ is a parameter that changes with the optical properties of the water body, with a value between 0.32 and 0.37, $n$ is the refractive index of water, and $t^2/n^2$ is approximately equal to 0.54. The ratio of $f$ to $Q$ is independent of the zenith angle $\theta$ and wavelength $\lambda$, only related to the water body [21]. $a(\lambda)$ and $b_b(\lambda)$ are the total absorption coefficient and total scattering coefficient of various substances in the water body. They are inherent optical properties of the water body, which only depend on various water quality parameters in the water. Thus, the reflectance equation can be simplified to the second form [4,22,23].

The water quality inversion from remote sensing mainly focuses on parameters such as chl-a, colored dissolved organic matter (CDOM), and the total suspended (TSS), because their spectral characteristics are obvious. According to Equations (1) and (2), the relationship between the water quality concentration and the radiance received by the sensor can be established, which has been verified by many studies [8].

$$L_w \propto f(chl - a, CDOM, TSS\ and\ others) \tag{3}$$

The optical properties of TP and TN are not obvious, and standard physical models cannot be used to construct their concentration estimation equations. However, many scholars have found a strong correlation between the concentrations of TN and TP and the concentrations of chlorophyll, CDOM, and TSS. The relationship between TN and TP and remote sensing data can be established indirectly as follows [11,24,25].

$$TP \text{ or } TN \propto f(chl-a, CDOM, TSS \text{ and others}) \propto L_w \tag{4}$$

In actual situations, parameters such as $a$ and $b_b$ are difficult to accurately measure, and the data of each lake are different. Therefore, empirical methods are generally established. The empirical models commonly used in previous studies include linear regression models and multiple regression models. A multiple regression model will yield some abnormal values that are too large or too small when estimating water quality parameters, so the linear regression model was selected for inversion in this study. The linear regression model was divided into a linear function and a quadratic function [9]:

$$P_{WQ} = F_1 \times B + F_2 \tag{5}$$

$$P_{WQ} = F_3 \times B^2 + F_4 \times B + F_5 \tag{6}$$

where $P_{WQ}$ is the water quality parameter, $F_1$ to $F_5$ are the unknown parameters, and B is the most relevant band combination selected. The accuracy of the quadratic function is generally higher than that of the linear function. However, sometimes, they are almost the same, so the linear function was selected to reduce the amount of calculation.

The empirical statistical models were developed based on in-situ water quality parameters and Landsat 8 remote sensing spectral data. Two thirds of the in-situ data were used as modeling data and the other one third were used as test data to evaluate the accuracy of the model. First, the correlation coefficients between each band and water quality parameters were calculated based on Pearson correlation analysis, as shown in Table 2. Then, the bands with high correlation with TN or TP were combined, such as (B1 + B2), (B1/B2), (B1 − B2)/B3, Ln(B1), etc. Subsequently, a selection of the optimal band combination was performed by the exhaustive method, which allowed us to establish a high-accuracy inversion regression model of the water quality parameters for each lake.

**Table 2.** The correlation coefficients between bands and water quality parameters.

| Lake | Parameters | B1 | B2 | B3 | B4 | B5 | B6 | B7 |
|---|---|---|---|---|---|---|---|---|
| Poyang | TP | 0.5440 | 0.4430 | 0.5407 | 0.8132 | 0.4185 | 0.3679 | 0.3798 |
| | TN | 0.2656 | 0.3954 | 0.6096 | 0.7379 | 0.2081 | 0.0023 | 0.0012 |
| Dongting | TP | 0.0584 | 0.2275 | −0.2405 | 0.4904 | 0.2379 | 0.3279 | 0.2842 |
| | TN | 0.4840 | 0.7266 | 0.2937 | 0.5723 | 0.7794 | 0.4384 | 0.3962 |
| Taihu | TP | 0.1059 | 0.2922 | 0.0520 | 0.3254 | 0.6996 | 0.3472 | 0.3292 |
| | TN | −0.4935 | −0.5751 | −0.8015 | −0.5215 | −0.3015 | 0.1044 | 0.5993 |

The accuracy of the regression model was evaluated by the root mean square error (RMSE), coefficient of determination ($R^2$), and mean relative error (MRE) [25].

The Pearson correlation coefficient was used to measure the linear relationship between two sets of data. The formula for the calculation of the coefficient is as follows:

$$r = \frac{\sum(X-\overline{X})(Y-\overline{Y})}{\sqrt{\sum(X-\overline{X})^2 \sum(Y-\overline{Y})^2}} \tag{7}$$

where $X$ is the value of the band combination, $\overline{X}$ is the average of all band combinations, $Y$ is the concentration of TN or TP, and $\overline{Y}$ is the average of all TN or TP data.

RMSE is the error between the observed value and the regression value, $R^2$ is the degree of the regression model fitting, and MRE is a percentage of relative error. The formulas for the calculation of RMSE, $R^2$, and MRE are as follows [26]:

$$\text{RMSE} = \sqrt{\frac{\sum(X_{value} - X_{model})^2}{n}} \tag{8}$$

$$R^2 = 1 - \frac{\sum(X_{model} - X_{value})^2}{\sum(X_{model} - \overline{X_{value}})^2} \tag{9}$$

$$\text{MRE} = \frac{1}{n}\sum\frac{|X_{model} - X_{value}|}{X_{value}} \tag{10}$$

where $X_{model}$ is the concentration of water quality parameters from the regression equation, $X_{value}$ is the measured concentration of in-situ water quality parameters, $\overline{X_{value}}$ is the average value of the measured water quality parameter concentration, and n is the total number of in-situ measured points.

## 4. Results and Analysis

The inversion model is affected by many local water environmental factors, such as chl-a, TSS and CDOM concentrations, TP and TN concentrations, aquatic organisms, etc. Various expressions were tested for each lake independently and the best one based on the statistical empirical method was used. The optimal band combination was selected to establish an inversion model based on the above evaluation indicators. The inversion model and accuracy indicators are shown in Table 3. The correlation coefficient of the optimal band combination of TP concentration in Dongting Lake was only 0.7530, and the correlation coefficients of the optimal band combinations of TN and TP in the three lakes were all above 0.8. This shows that the band combinations had a strong correlation with the water quality parameters.

**Table 3.** Water quality inversion model and accuracy of TN and TP in three lakes.

| Lake | Parameters | Regression Equation | RMSE (mg/L) | $R^2$ | MRE |
|---|---|---|---|---|---|
| Poyang lake | TP | $-5.3248 \times \ln(B4)/B4 + 0.0885$ | 0.0048 | 0.7589 | 90.98% |
| | TN | $0.233 \times (B4 - B1)^2 + 1.2714 \times (B4 - B1) + 1.3499$ | 0.1252 | 0.7970 | 93.40% |
| Dongting lake | TP | $0.0038 \times ((B4 - B3)/B5)^2 + 0.0146 \times (B4 - B3)/B5 + 0.0772$ | 0.0042 | 0.5816 | 95.54% |
| | TN | $0.5914 \times (B5 + B2) + 1.1997$ | 0.1476 | 0.6529 | 94.00% |
| Taihu lake | TP | $0.0292 \times (B5/B1)^2 + 0.0979 \times (B5/B1) + 0.0332$ | 0.0326 | 0.7122 | 75.30% |
| | TN | $-3.219 \times (B3 - B7) + 5.712$ | 0.4751 | 0.7452 | 83.57% |

The water quality inversion regression models of TN and TP concentrations for each lake were established (Table 2) and the accuracy of the model was evaluated, as shown in Figure 2. The RMSE value was related to the size of the parameter, the TP concentration was approximately 0.3 mg/L, and the RMSE was 0.0048. The concentration of TN ranged from 1 mg/L to 5 mg/L, so the RMSE was relatively large. $R^2$ is a dimensionless coefficient and is not affected by the size of the parameter. The lowest correlation coefficient was the TP inversion model of Dongting Lake, and its $R^2$ was also the lowest, at 0.5816. However, the $R^2$ values of the other inversion regression models were between 0.6 and 0.8, showing that the inversion models had a high degree of fitting [27].

The monthly TN and TP concentration distribution maps of each lake were derived from the inversion models in Table 3, and the temporal and spatial characteristics of the water quality of each lake were analyzed.

### *4.1. Spatial-Temporal Variations in TN and TP in Poyang Lake*

The water quality of Poyang Lake was retrieved based on Landsat 8 remote sensing images, and the monthly average water quality concentrations were counted. For some months, there were no available images due to cloud cover, and the average concentration was calculated by an interpolation method, as shown in Figure 3. The monthly average concentration of TN in Poyang Lake ranged from 1.278 mg/L to 2.137 mg/L, with the minimum concentration appearing in July 2017 and the maximum concentration appearing in March 2017. The monthly average concentration of TP ranged from 0.031 mg/L to 0.061 mg/L, with the minimum value appearing in August 2019 and the maximum value appearing in January 2014. From 2014 to 2020, the temporal variation characteristics of the TN and TP concentration in Poyang Lake were very similar, showing a sinusoidal fluctuation distribution. A low water quality concentration was measured from June to September each year, and a higher water quality concentration was measured from November to March of the following year, which means that the water quality concentrations were higher in winter and spring and lower in summer. The annual average concentrations of TN and TP showed a downward trend. According to the trend line over the past 7 years, the average concentration of TN has decreased by 5.99%, and the average concentration of TP has been reduced by 7.13%.

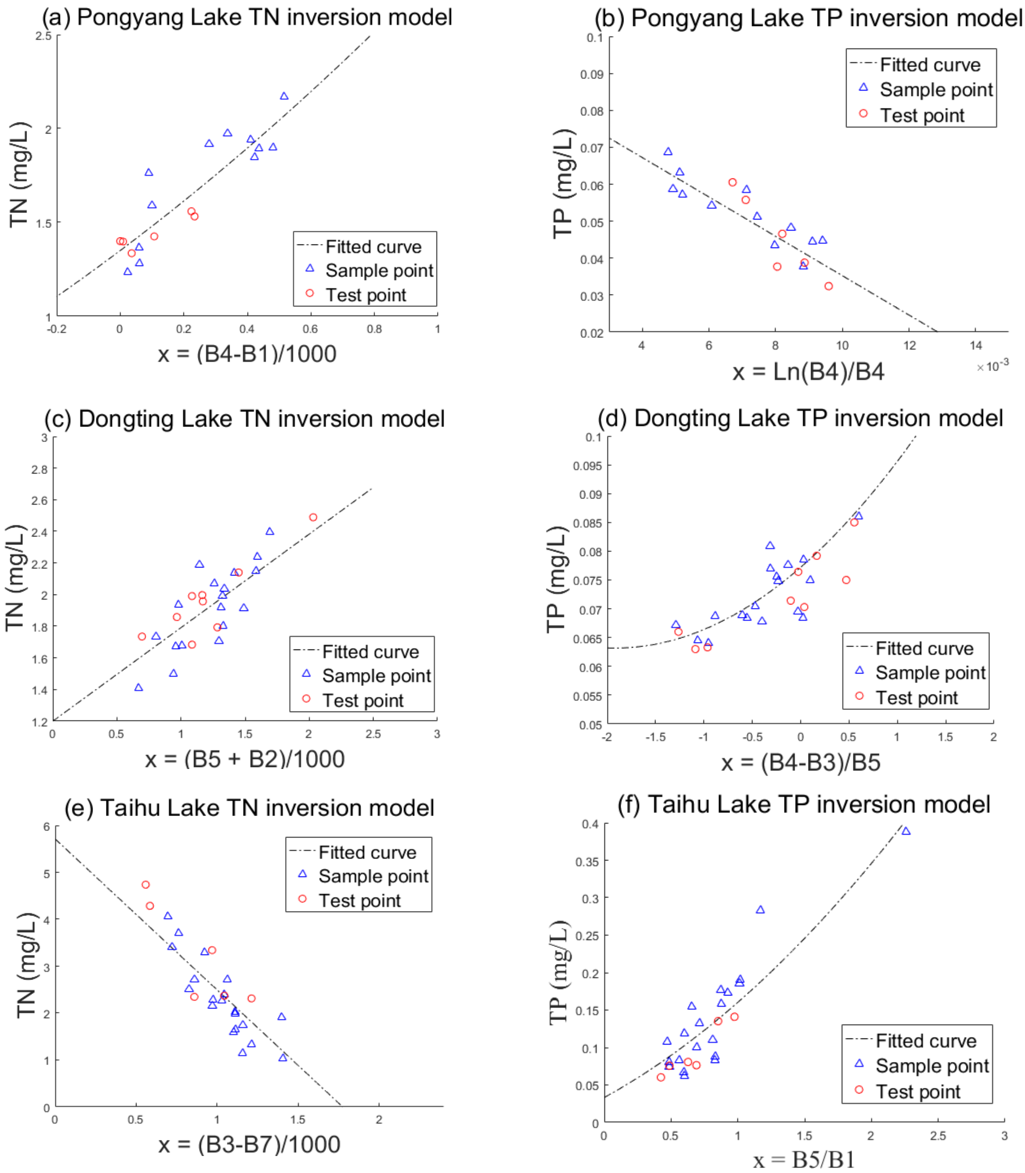



**Figure 2.** Inversion regression model of TN and TP in each lake.

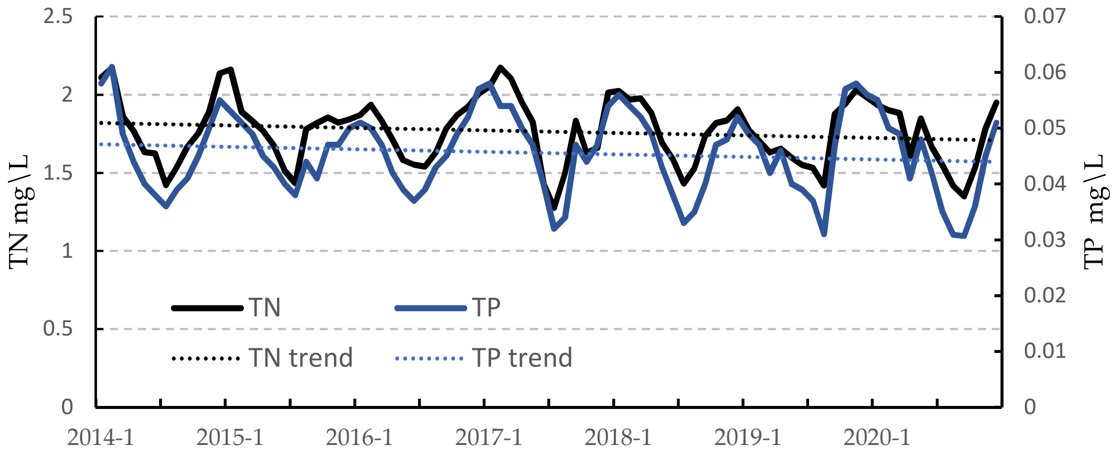



**Figure 3.** Trends of average monthly concentration variations in TN and TP in Poyang Lake from 2014 to 2020.

The average water quality concentrations of the lake were retrieved for each quarter and the temporal and spatial distribution characteristics of water quality were analyzed, as shown in Figure 4. In general, the TN concentration in the northern part of the lake was higher and lower in the southern lake. The TN concentration in spring and winter was higher than that in summer and autumn. In the spring and winter seasons, the TN concentration was higher in the northern lake, the eastern delta, and the river entrance to the lake. However, in the summer and autumn, a higher concentration was found in the northern and middle parts of the lake. The temporal variation in TP in Poyang Lake was similar to that of TN, but the spatial variation gradient of TP was more significant. In winter, the water area of the entire lake decreased, and the concentrations of TN and TP increased. The pollutants were dispersed from the entrances of rivers into the lake and were scattered in a plane. In summer, the lake area is large and the total concentration of nutrients is low. The nutrients concentration of the Yangtze River into the lake channel was high during the studied period, and it spread from the channel entrance to the middle and then decreased near the surrounding area. The concentrations of TN and TP in Poyang Lake were the lowest among the three lakes [28].

### *4.2. Spatial-Temporal Variations in TN and TP in Taihu Lake*

The trend of water quality variations in Taihu Lake is shown in Figure 5. The monthly average concentration of TN in Taihu Lake ranged from 1.67 mg/L to 2.82 mg/L, with the minimum concentration appearing in July 2018 and the maximum concentration appearing in November 2020. The monthly average concentration of TP ranged from 0.074 mg/L to 0.151 mg/L, with the minimum value appearing in January 2018 and the maximum value appearing in August 2017. From 2014 to 2020, the TN concentration of Taihu Lake showed fluctuations, being higher in spring and winter but lower in summer. The temporal variation in the TP concentration showed the opposite trend to that of TN, being higher in summer and lower in spring and winter. In the past seven years, the average concentration of TN has changed little, and the trend is basically flat. However, the trend of the average concentration of TP has increased by 17.3% as of January 2021 when compared to January 2014.

The seasonal variations in TN and TP in Lake Taihu are shown in Figure 6, which shows that the spatial distribution characteristics of TN and TP were similar for the studied period. In general, the water quality concentration of the lake was higher in the west than in the east, especially in the northwest, where the rivers enter the lake. The water quality in the center of the lake was better, but the lake area in the southeast exceeded the standard. The spatial distribution of the TN concentration also showed a difference between the north and the south. The TN concentration in the north was higher than that in the south, especially in the spring and winter.

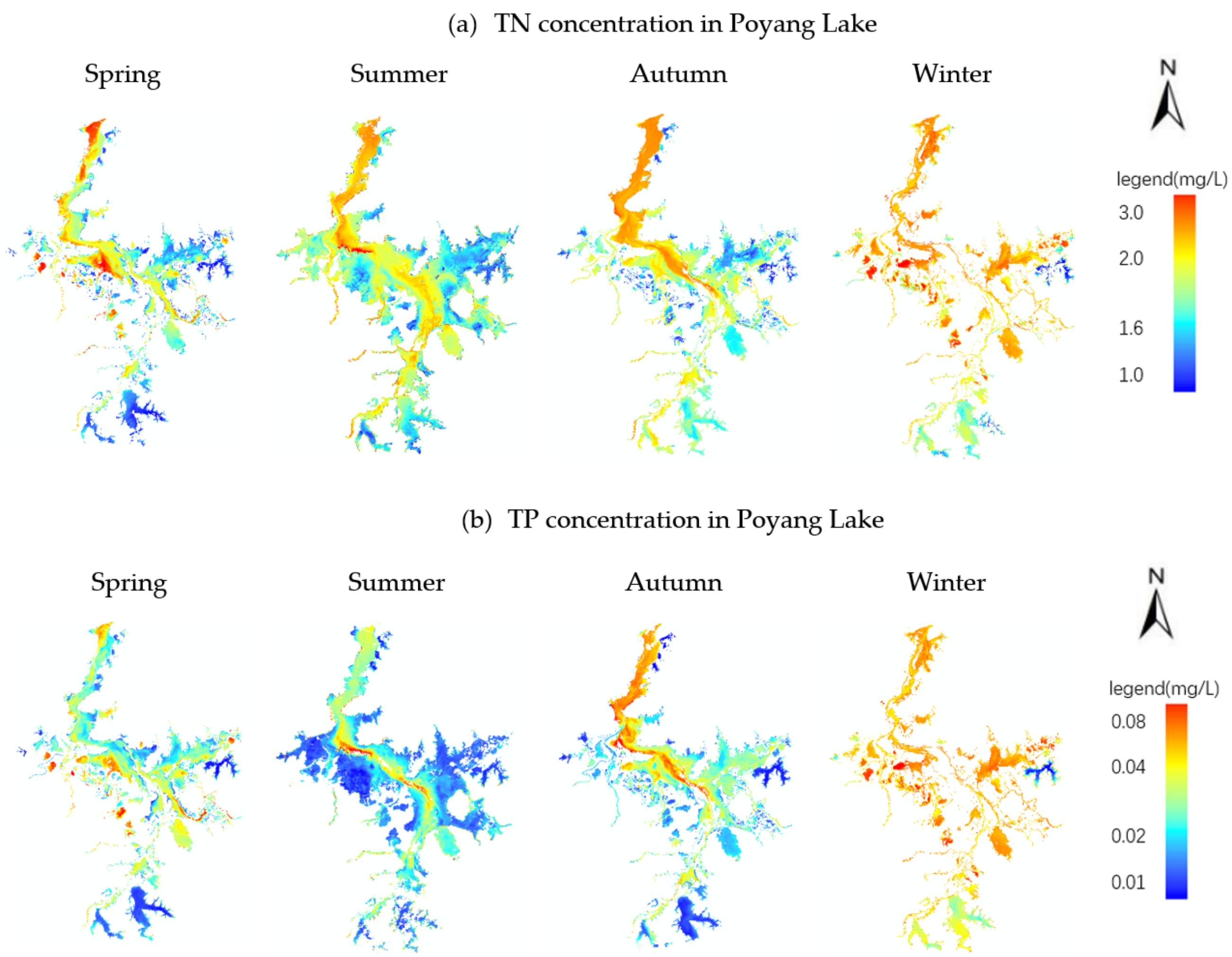



**Figure 4.** Seasonal variations in water quality concentration in Poyang Lake.

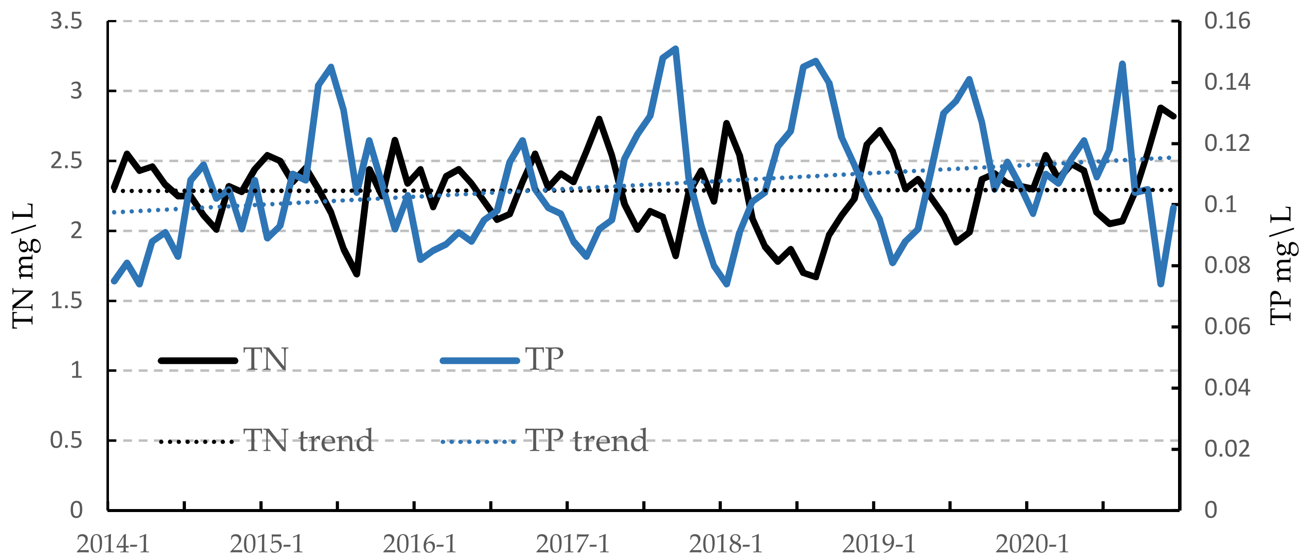



**Figure 5.** Trends of average monthly concentration variations in TN and TP in Taihu Lake from 2014 to 2020.

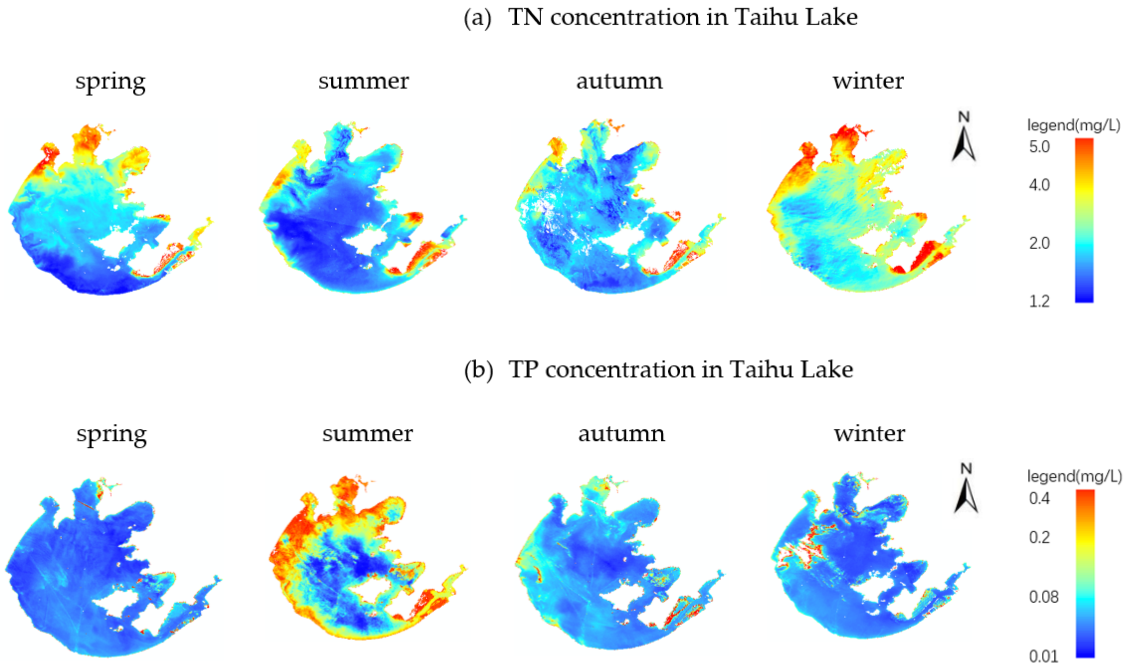



**Figure 6.** Seasonal variations in water quality concentration in Taihu Lake.

In comparison, pollution in the northwestern lake entrance was more severe, and the TN concentration in the southwest of the lake was relatively low. The TN in the southeast entrance of the lake showed a consistently high concentration, which may have been due to the paddy field causing errors in the image inversion. The temporal and spatial distribution of TP differed from that of TN. In summer, the overall concentration of TP was higher, and the levels at the lake entrances of the river in the northwest were significantly higher than in other regions, spreading from the west to the center. In the spring and winter, the TP concentration in the lake was generally low, and the spatial distribution was relatively balanced, while the TP concentration in the western part was slightly higher than in other regions [29,30].

### *4.3. Spatial-Temporal Variations in TN and TP in Dongting Lake*

Regarding the water quality of Dongting Lake (Figure 7), the monthly average concentration of TN ranged from 1.619 mg/L to 2.416 mg/L, with the maximum value appearing in December 2020 and the minimum concentration appearing in July 2020. The monthly average concentration of TP ranged from 0.073 mg/L to 0.11 mg/L, with the minimum value also appearing in July 2015 and the maximum value appearing in January 2019. From 2014 to 2020, the TN in Dongting Lake fluctuated cyclically, with a peak between November and March each year and the lowest value recorded around July. The temporal variation trend of TP was similar to that of TN, but the overall concentration of TP in Dongting Lake was low, as was the annual change range. The variation trend of the yearly average concentrations of TN and TP in Dongting Lake is decreasing. During the seven-year period, the average annual concentration of TN decreased by 5.25%, while the decrease in TP was less than 1%.

The seasonal variations in TN and TP in Dongting Lake are shown in Figure 8. The spatial distribution of TN concentration was generally greater in the east than in the west. Moreover, the temporal change in the concentration was higher in winter and conversely lower in summer. The concentration of TN at the entrance of the Yangtze River in the north of Dongting Lake was low, especially in summer, which is evidenced by the fact that the water from the Yangtze River flows into the lake to form a fan spread, and the concentration along the lakeshore is greater than in the center of the lake. In spring and winter, the water area decreased, the lake surface became narrower, and the TN concentration gradually increased from the middle of the lake to both sides. The temporal change in TP was similar to that of TN. The spatial distribution of TP was also low at the mouth of the Yangtze River, while the TP concentration on the shore was relatively high. Unlike TN, the TP concentration in the west of the Dongting Lake was greater than that of the east. The average concentrations of TN and TP in Dongting Lake were approximately similar to the mean concentrations of the three lakes [31,32].

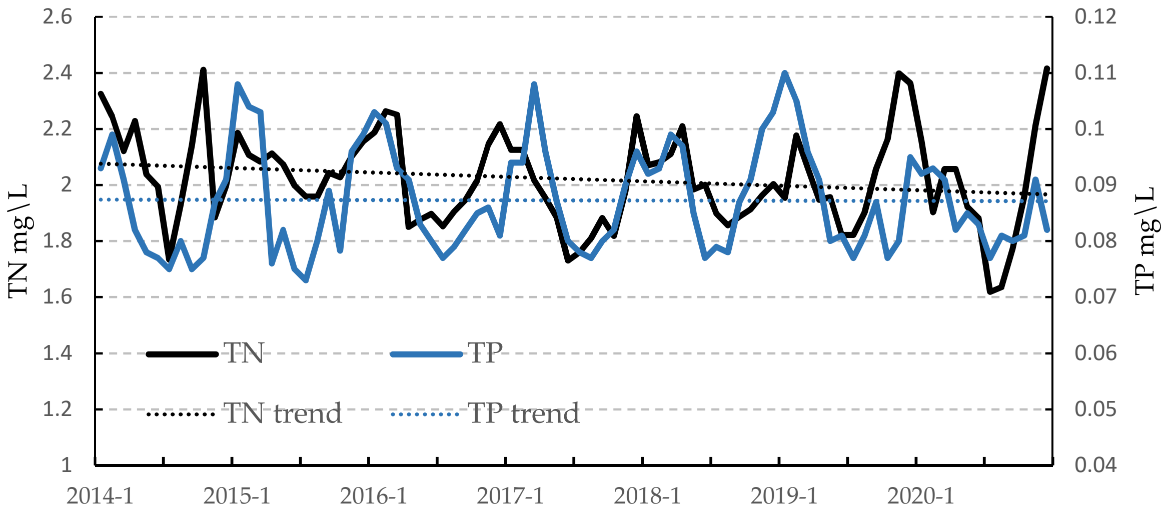



**Figure 7.** Trends of average monthly concentration variations in TN and TP in Dongting Lake from 2014 to 2020.

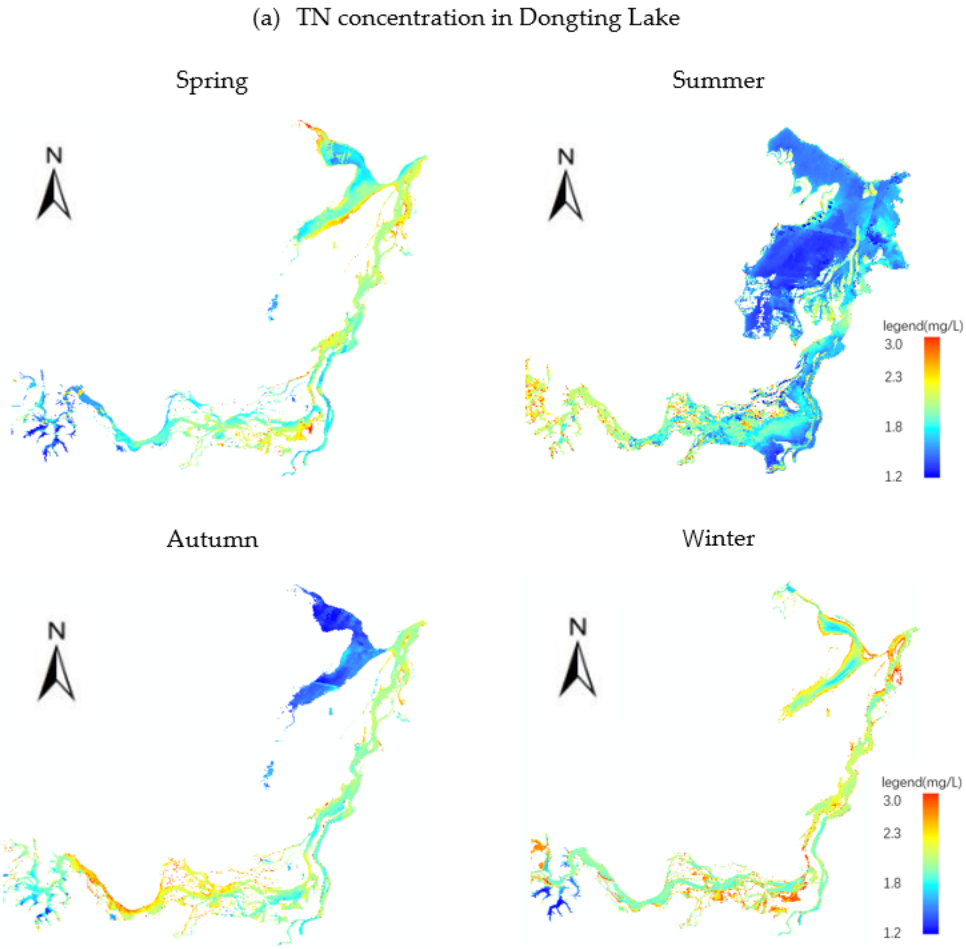



**Figure 8.** *Cont.*

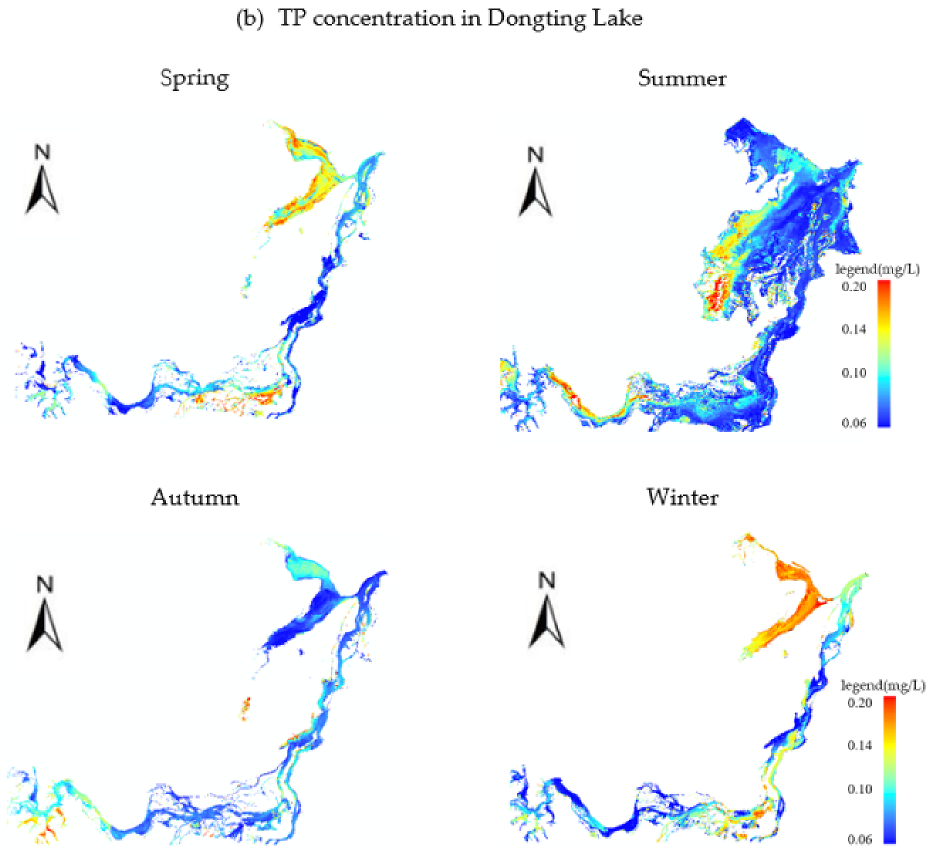



**Figure 8.** Seasonal variations in water quality concentration in Dongting Lake.

*4.4. Comparison of TN and TP Variations in Three Lakes*

The statistics of the average TN and TP concentrations in each quarter of the three lakes in the 7 years from 2014 to 2020 are shown in Figure 9. The concentration of TN in Poyang Lake was relatively small, while the pollution of TN and TP in Taihu Lake was more severe and the degree of eutrophication was also the highest among the three lakes. The difference in TN concentration in the three lakes was relatively small. The TP concentration in Taihu Lake has always been more significant than in Dongting Lake and Poyang Lake. The seasonal changes in the TN concentration in the three lakes were the same, with the lowest values occurring in summer and the highest in winter. The difference in the TP concentration in the three lakes was even more remarkable. The seasonal variation in TP concentration in Poyang Lake and Dongting Lake was almost the same, with the lowest value occurring in summer and the highest in winter. However, the TP concentration in Taihu Lake was the highest in summer and the lowest in winter. Only in winter, the TP concentration in Dongting Lake exceeded that in Taihu Lake and became the highest among the three lakes.

Poyang Lake and Dongting Lake are the largest lakes connected to the Yangtze River. The flow and circulation of water in these lakes are much greater than in Taihu Lake. The water levels of the two lakes vary with the Yangtze River, and the difference between the dry season (November to February of the following year) and the wet season (June to August) is very high. The water level of Dongting Lake reached a peak of 33.5 m during the flood period in July 2020 when compared to 20.1 m during the dry season. The water level of Poyang Lake also reached a maximum of 21 m in July 2020, and only 7.45 m during the dry season, as shown in Figure 10. The trends of the concentration variations in TN and TP in the two lakes are similar, and the monthly average TN and TP concentrations in the lakes are inversely proportional to the monthly average water level. Unlike the two lakes, Taihu Lake is a plain shallow lake, which does not connect with large rivers. The average annual water level is generally around 3 m and the maximum annual water level difference does not exceed 1 m. The lake water cycle is slow and nutrients are deposited easily, so the water level has a slight effect on the concentrations of nutrients in Taihu Lake. However, the seasonal variations in TN and TP in the lake are still pronounced. The concentration of TN is low in summer and high in spring, while the TP concentration is highest in summer and low in spring. In summer, the temperature rises, the precipitation increases, and aquatic plants grow in abundance. Because the water level of Lake Taihu is very shallow, precipitation and plant growth disturb the bottom sludge of the lake, causing a large amount of nitrogen and phosphorus substances to be released into the water. In addition, nutrients in farming areas flow into the river with the precipitation and finally into Lake Taihu, which causes the concentration of nutrients in the water to increase. However, plant growth consumes far more nitrogen than phosphorus, so the TN concentration in summer does not increase. In autumn and winter, aquatic plants die and decompose to release nitrogen, which increases the TN concentration in winter.

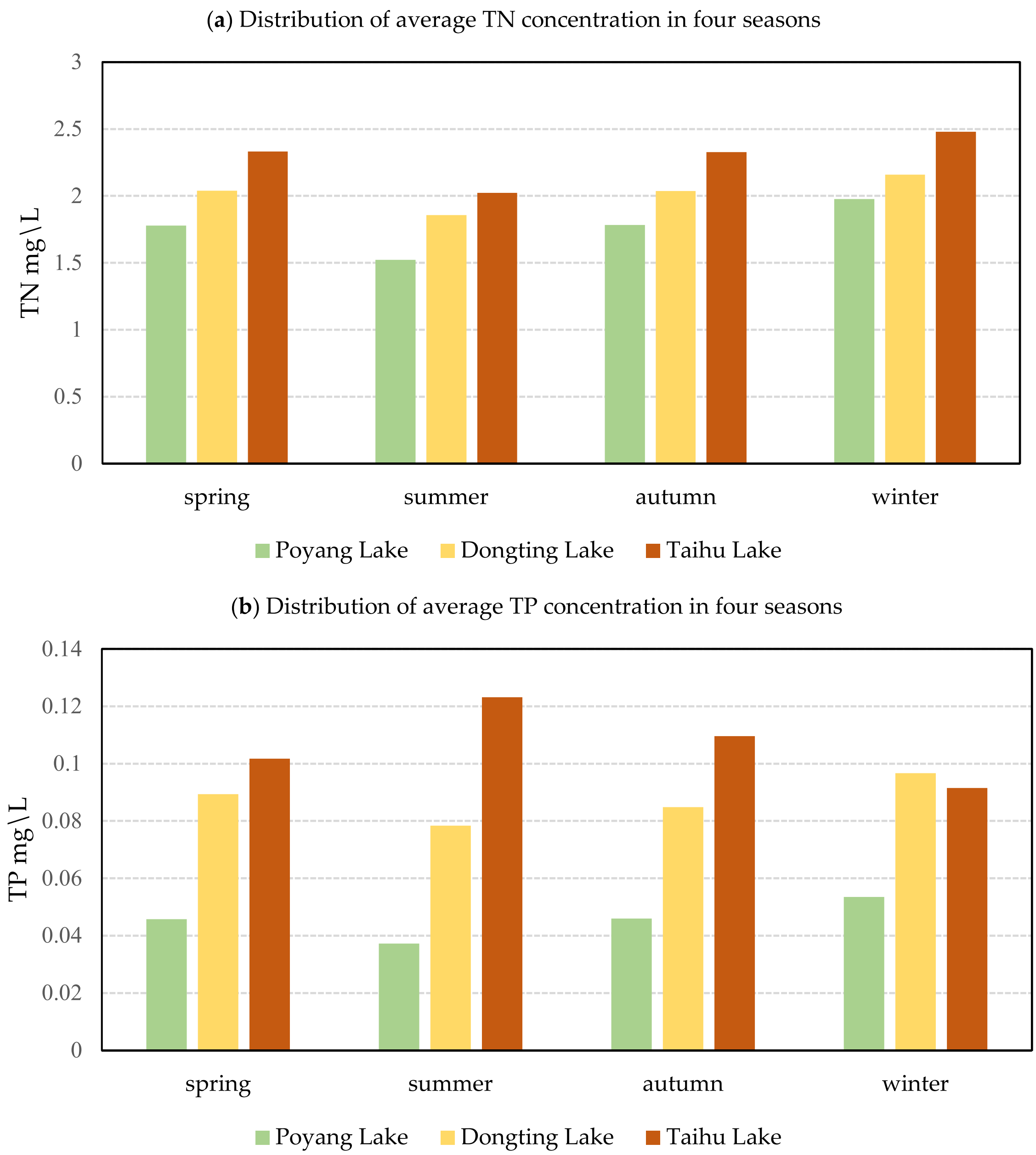
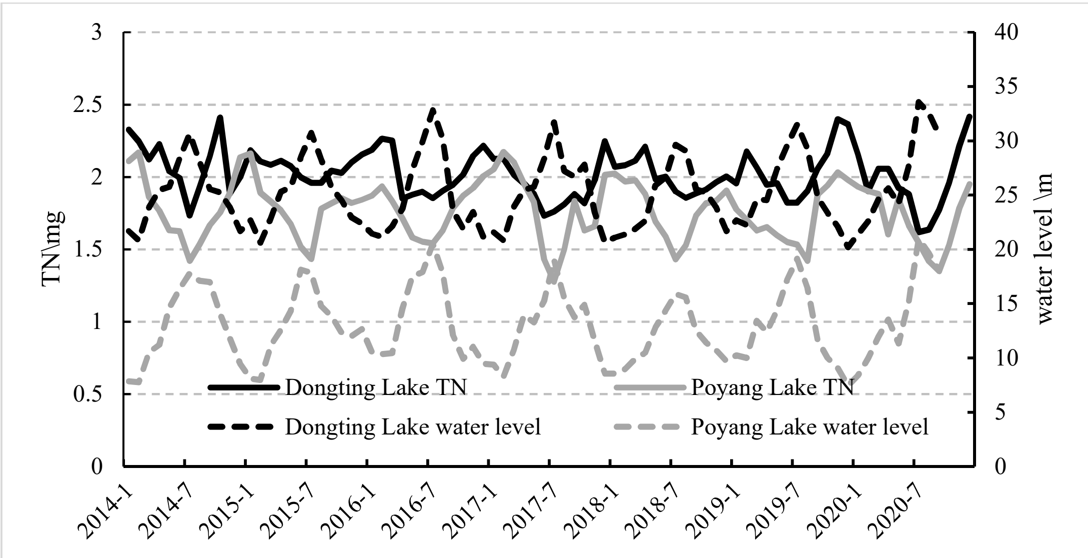



**Figure 9.** Average TN and TP concentrations of the three lakes in four seasons from 2014 to 2020.

(**a**) Monthly average water level and TN concentration




(**b**) Monthly average water level and TP concentration

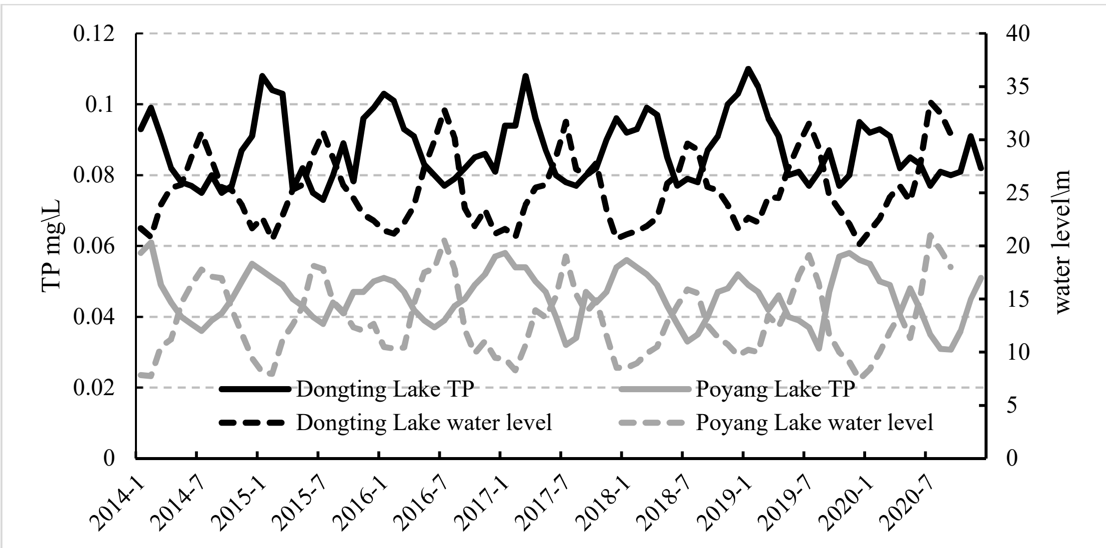



**Figure 10.** Comparison between the water level and the concentration of TN and TP in Poyang Lake and Dongting Lake.

The spatial distribution of TN in the three lakes is different, but the TN concentration is higher at the lake entrance than the lake outlet. The water system of Taihu Lake flows from west to east, and the concentrations of TN and TP at the western entrance of the lake are more significant than those at the eastern outlet of the lake. The concentrations of nitrogen and phosphorus are also higher where the rivers flow into Dongting Lake and Poyang Lake. During the dry season, the TN and TP concentrations of Poyang Lake and Dongting Lake at the mouth of the Yangtze River are at a high level throughout the whole lake. During the dry season, when the water carries nutrients from Poyang Lake and Dongting Lake into the Yangtze River, the concentrations of TN and TP in the area connecting the two lakes and the Yangtze River are high throughout the whole lake. During the wet season, the water flows from the Yangtze River into Poyang Lake and Dongting Lake, and the concentrations of TN and TP in the area connecting Dongting Lake and the river are low, but remain high in Poyang Lake. This might be due to the fact that an important shipping harbor is located at the connection between the Yangtze River and Poyang Lake. The water level of Poyang Lake is lower than that of Dongting Lake, so it is more susceptible to the influence of shipping activities, resulting in high nutrient concentrations. Another reason is that the TN and TP contents of the Yangtze River are higher than that in the lake, which also leads to an increase in the TN and TP concentrations [33,34].

## 5. Discussion

Poyang and Dongting Lakes are directly connected with the mainstream of the Yangtze River. The lakes have a high-water velocity, a large net flow, and a short water cycle (less than 20 days). In this hydrological environment, the nutrient retention coefficient is low and does not stabilize easily, so the eutrophication degree is low [35,36]. The middle and lower reaches of the Yangtze River are subject to the wet season in summer and the dry season in winter. The increase in rainfall and water from rivers improves the lake's water cycle efficiency and self-purification capacity in the wet season. A large amount of incoming water dilutes the lake, resulting in a decrease in the total concentration of pollutants [37]. During the dry season, the water level falls and the deaths of aquatic organism release TN and TP, which leads to an increase in the concentrations of lake nutrients. Taihu Lake is different from the other two lakes, and the water level and annual change are low, so the concentrations of TN and TP are not related to the water level. The lake water is collected from the surrounding surface runoff and the water change cycle is long, lasting 215 days in a wet year [38]. The lake's self-purification ability is weak, nutrients settle easily, and the concentrations of TN and TP in Taihu Lake are higher than in the other two lakes. In addition, the shallow water level of the lake causes the nutrients deposited in the bottom layer to be easily disturbed and absorbed by the surface plants, and algae grows rapidly, facilitating the formation of water blooms [39].

The change in water level are the main causes of the temporal variations in TN and TP in Poyang Lake [40]. The water level of Poyang Lake is higher during the wet season, and the nutrients concentrations are diluted and decreased. The water level decreases during the dry season, and the nutrient concentrations increase [41]. The water of Poyang Lake mainly comes from the five rivers and flows into the Yangtze River from south to north. These five rivers are adjacent to the agricultural land. Large amounts of nitrogen and phosphorus residues from chemical fertilizers used in agriculture are collected in the middle of the lake along the rivers and finally flow away through the Yangtze River via the northern lake. Therefore, the northern part of Poyang Lake and the tributaries into the lake accumulate a large amount of TN and TP, the concentrations of TN and TP are relatively high. The southern part has a more elevated terrain, and the nutrients do not settle easily, so the water quality is better. The nutrient concentration in northern channel is very high. The main reason is that a large number of cargo ships in the port disturb the bottom mud of the lake and release the deposited pollutants into the water. Furthermore, there are many cities on both sides of the port, and the discharge of urban sewage and industrial wastewater has caused an increase in the TN and TP concentrations [42]. The nutrients concentrations in the center of Poyang Lake increase during the dry season, disturbing the bottom of the lake by lowering the water level. Another reason is that the aquatic organisms in the lake die and decompose, releasing nitrogen and phosphorus into the water [43].

TN and TP changes in Dongting Lake are similar to Poyang Lake. The water from the Yangtze River flows into Dongting Lake during the wet season. The lake water feeds back into the Yangtze River during the dry season and raises the water level of the Yangtze River. The water level of Dongting Lake is higher than that of Poyang Lake, and the area where the river enters is vast, so the bottom mud of the lake is not easily disturbed by shipping activities. A large amount of water from the Yangtze River flows into Dongting Lake during the wet season. Although the total contents of nitrogen and phosphorus increase, their concentrations decrease [44]. The water quality concentrations in the northern part of the lake show a significant decrease. During the dry season, the lake water conversely flows into the Yangtze River. The TP concentration at the lake's outlet in 2014 and 2015 was greater than in the surrounding area, indicating that the phosphorus that had accumulated in the lake entered the Yangtze River. The TN and TP in Dongting Lake mainly result from pollution caused by human activities in the surrounding area. The southern part of the lake is an important agricultural base. The large industrial bases, including the western part, are home to highly polluting industries, such as the papermaking and fertilizer industries. The eastern part is home to a large town in Hunan Province, which produces a large amount of domestic sewage. In addition, the completion of the Three Gorges Project has reduced the water circulation of the lake and increased the nutrients concentrations [15,45]. In recent years, the annual average nutrients concentration trends show that the pollution of Dongting Lake has been slightly improved.

The annual water level changes in Taihu Lake are small, and there is no strong correlation with the nitrogen and phosphorus substances in the lake. The changes in the lake nutrients concentrations are affected by the combined effects of temperature, precipitation, and human activities. The temporal variations in TN and TP in Lake Taihu show the opposite trend. The concentration of TN is lower in summer and higher in spring, while the TP concentration is the highest in summer and the lowest in spring. Nitrogen is essential for the growth of algae in the water. In summer, the temperature rises and the plants in the water grow faster, which dramatically improves the denitrification capacity of the lake, resulting in a decrease in the TN concentration [39]. Simultaneously, the application of chemical fertilizers in spring cultivation also increased the input of nitrogen into the lake [30]. In summer, water blooms erupt in Taihu Lake, and the massive growth of algae releases the TP at the bottom of the lake into the water, increasing the concentration of TP. In addition, the increase in precipitation also brings nutrients from the agricultural fields surrounding the lake, leading to an increase in the TP concentration [38,46]. Numerous rivers carry a large amount of nitrogen and phosphorus substances into the lake from the west of Taihu Lake. Therefore, the concentrations of TN and TP in the west are always higher than in other zones of the lake, e.g., the eastern part [47]. However, the concentrations of nutrients along the coast of the southeast lake area are high because there are many fishing grounds along the coast, leading to poor results.

## 6. Conclusions

The water quality parameters of TN and TP were inversed based on empirical models from ground observation data and Landsat 8 OLI remote sensing images at the three major lakes, Poyang Lake, Dongting Lake, and Tai Lake, in the middle and lower reaches of the Yangtze River. The model coefficients of determination $R^2$ reached 0.6–0.8 and the relative accuracies were above 75%. Furthermore, the variations in the TN and TP concentrations in the three major lakes from 2014 to 2020 were analyzed using the spatial-temporal analysis method. The concentrations of TN and TP were relatively high in Lake Taihu, with an increase in the past seven years, and relatively low in Poyang Lake and Dongting Lake, with a decrease in the past seven years. The temporal and spatial variations in TN and TP in Poyang Lake were similar and the concentrations were low in the wet season and high in the dry season. The northern port road that connects with the Yangtze River was heavily affected by human activities and the concentration was relatively high. The concentration of nutrients at the entrance of the five rivers was relatively high. The temporal trend of the concentrations of TN and TP in Dongting Lake was similar to that of Poyang Lake, and the concentration was low during the wet season and high during the dry season. The changes in TN and TP in Poyang Lake and Dongting Lake were mainly the result of human activities and the water level of the Yangtze River. There were apparent differences in the temporal trends of TN and TP in Lake Taihu. The concentration of TN was lower in summer and higher in spring, while the concentration of TP was higher in summer and lower in spring. The spatial distributions of nutrients were similar, with higher concentrations at the entrances of rivers in the west and lower concentrations at the lake center and the eastern lake outlet.

The long-term TN and TP contents in the three lakes were retrieved by remote sensing. The inversion accuracy was validated by comparison with other studies, and the spatial-temporal distribution characteristics and influencing factors were analyzed. However, due to the short time scale and sparsity of in-situ data, the results of the study still carry uncertainty. In the future, we will continue to improve our inversion model and monitor lake water quality variations with more in-situ data for the three major lakes in the middle and lower reaches of the Yangtze River.

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