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Assessment of Lake Water Quality and Eutrophication Risk in an Agricultural Irrigation Area: A Case Study of the Chagan Lake in Northeast China

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Abstract: Water quality safety is the key factor to maintain the ecosystem service functions of lakes. Field investigations and statistical analyses were carried out to study the water quality of a large, agriculture-stressed lakes (e.g., Chagan Lake) in Northeast China. The hydro-chemical properties of the Chagan Lake are $HCO_3 \cdot CO_3$-Na. Nutrient (N and P) and non-nutrient (pH and F^-) were found to be the major factors that threaten water quality safety of the lake. The concentration of total nitrogen (TN) and total phosphorus (TP) was found to vary seasonally and at different locations. The overall lake water had mean TN and TP values of 2.19 mg/L and 0.49 mg/L, respectively, in summer. TN was the major factor for water quality deterioration in the western region of the lake, while TP was the principal factor in the other regions, as determined by a principal component analysis (PCA). Fluoride (F^-) concentration in the lake water were related to the values of total dissolved solid (TDS), pH, and electrical conductivity (EC). In addition, eutrophication is a fundamental index that has been affecting the ecological evaluation of water quality. The results showed that trophic level index (TLI), trophic state index (TSI), and eutrophication index (EI) were evaluated to quantify the risk of eutrophication. However, TLI and TSI can better describe the purification effect of the wetland. These indices showed that the lake water was hyper-eutrophic in summer, with TLI, TSI, and EI values of 60.1, 63.0, and 66.6, respectively. Disparities in water quality were observed among whole areas of the lake. Overall, this study revealed that controlling agriculture drainage is crucial for lake water quality management. The study generated critical data for making water quality management plans to control the risk.

Keywords: eutrophication; agriculture-stressed; nutrients; water quality; Chagan Lake

1. Introduction

Eutrophication has caused a series of water quality problems for freshwater and marine ecosystems, which are caused by the response of natural waters to an excessive input of nutrients [1–3]. The effect of eutrophication on global warming and growing human populations act in concert with increasing nutrients, especially in recent decades [4–8]. Systematic water quality monitoring, risk assessment, and preventative measures are important tools adopted by environmental protection agencies to tackle the problem of lake eutrophication.

Over the past decades, studies of eutrophication have evolved from problem definitions to the identification of causes, and then on to water quality management. Excessive loading of nitrogen or phosphorus break the balance of Redfield ratio N:P of 16:1, which result in algal blooms, fish kills, and many related problems [9–11]. Human activity had accelerated the eutrophication process by the mid-twentieth century [3,12]. The problem was found to be more intense with growing populations around the lakes. Vanni and Temte [13] revealed that seasonal variation in the strength of grazing in eutrophic lakes determine phytoplankton seasonal succession. Even in the high arctic, eutrophication occurred at sites where prehistoric Inuit whalers butchered their prey on the shores of freshwater lakes [14]. Both global climate change and sediments influence the eutrophication of natural lakes [15,16]. As human populations increased, a large number of wetlands and saline-alkali land were transferred to irrigation fields. Nutrients flowed into the lake with irrigation drainage, resulting in accelerating eutrophication of lakes in agricultural areas [17–19]. In the scientific community, there is poor consensus on how to reverse eutrophication. Eutrophication of lakes cannot be controlled only by reducing nitrogen input, according to the results from a 37-year-old whole-ecosystem experiment [20]. In addition, the controversy over whether reversing eutrophication requires reducing input of phosphorus, or both phosphorus and nitrogen, has important scientific implications in water management practices around major lakes [2,3,21–23]. However, research finds that the natural need of people are now the greatest and the natural capacity to meet those needs is down, which is especially reflected in the changes of water quality in population gathering areas [24].

The trophic state index (TSI) is a widely used indicator to assess and define water quality. Proposed by Carlson [25] in the 1970s, this index method has been applied worldwide to assess the water quality of lakes [26–29]. In China, water quality of many lakes has deteriorated with economic development and growing populations. Due to the varied topographies, cultural environments, and human activities, the assessment methods of lake eutrophication in China are different for different regions, in that comprehensive trophic level index TLI ($\sum$) [30,31] are often applied to assess the conditions of water quality. The data for calculating these indicators are typically sourced from long-term experiments and satellite remote sensing [25,32]. To date, lake water quality studies in China have been conducted predominately in regions of the most rapid economic progress, such as the Yangtze River Basin [33–37], whereas the lakes in impoverished agricultural regions have rarely been studied for eutrophication risks. In recent years, elevated concentration of TN and TP has been found in the lakes in high-latitude Northeastern China, especially those surrounded by crop irrigation fields. There is an imperative to carry out water quality studies, initially on a case-by-case basis, to assess the eutrophication risk of these lakes and to prevent irreversible environmental damages from taking place.

Increasing irrigation districts with a large quantity of discharge threaten the water quality security and lead to the aggravation of eutrophication in the Chagan Lake. This study was launched in 2018 to obtain—(1) the spatial patterns of water quality indicators; (2) the three-types of integrated indicators to assess the risk of eutrophication of the lake resulting from excessive nutrients delivery in freshwater bodies surrounded by the agriculture-stressed fields; and (3) influencing factors analyze for the eutrophication of the lake using the principal component analysis (PCA). The study provides a scientific basis for maintaining the safety of ecosystem and promoting the development of ecological economics.

2. Materials and Methods

2.1. Study Area

Chagan Lake is located in Southeast China's Nenjiang River basin (Figure 1), which is the drainage area for commodity grain production base. It has an average annual precipitation in the range of 400–500 mm and the annual evaporations range 1140–1270 mm, which are significantly higher than the precipitation. The surface area of the lake is 372 km^2, with an average depth of 1.52 m, storing approximately 5.98×10^8 m^3 of water [38]. The major sources of water to the lake include the drainage from the surrounding irrigation fields, which make 63.4% of all water sources. Primarily discharged into the lake via a natural wetland (i.e., Xinmiao Lake), which is a shallow marsh wetland with a 35 km^2 surface area and a 0.5 m average water depth [39]. A substantial amount of N, P, and saline–alkali flow into the lake with irrigation discharge. The Chagan Lake area is divided into the western region (sites 1–3), middle region (sites 4–5, 10–12), eastern region (sites 6–9), the Maying Lake (13–15), and the Xinmiao Wetland (16–18).

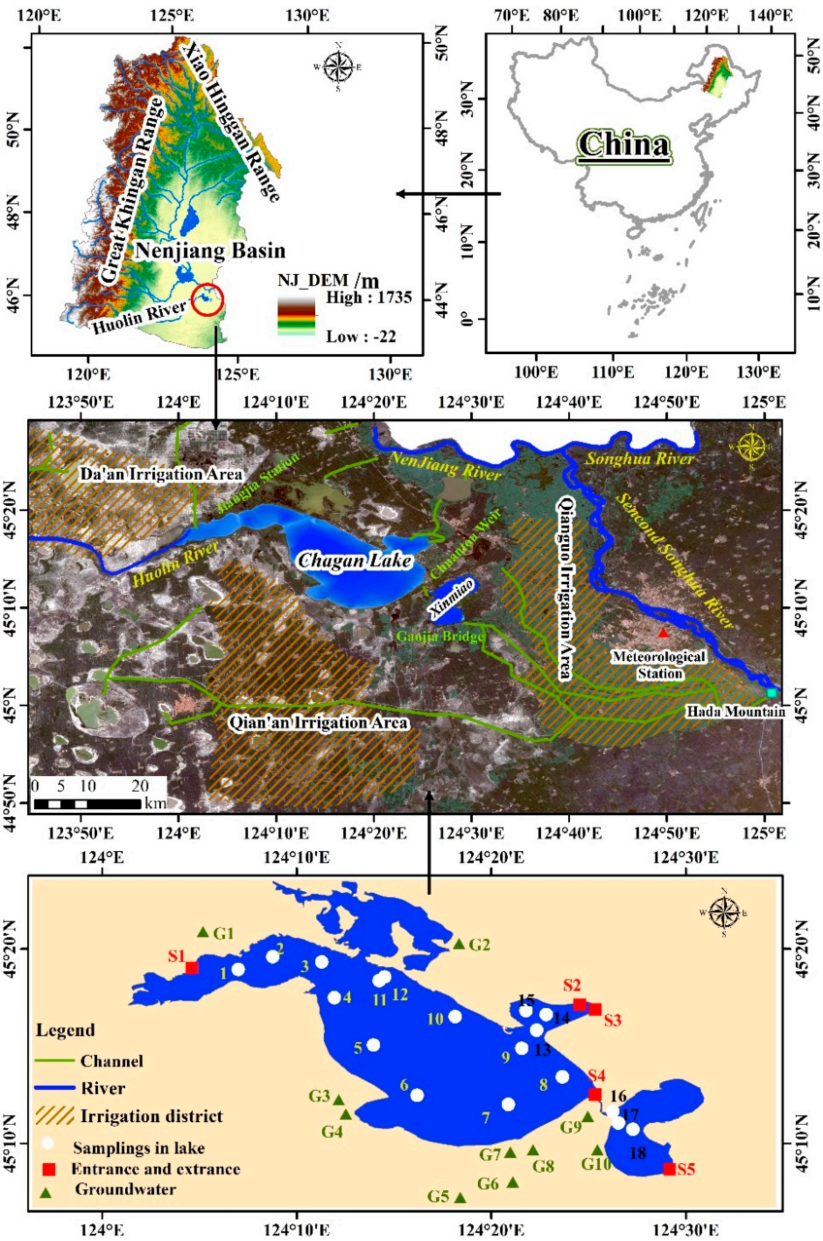

Figure 1. Study area and locations of water sample sites.

2.2. Water Sample Collection

The temperature (T), precipitation (P), and evaporation (E) in this area varies significantly with seasons, with 86.9% of the annual precipitation (based on 1960–2017 data) occurring during the period of May–September. Irrigation drainage into the lake also majorly takes place during this period. Therefore, water samplings were conducted during May to September. The water samplings we collected mixed evenly and vertically. As indicated in Figure 1, water samples were collected from thirty three sampling points located in the lake (i.e., points 1–18), in the groundwater wells around the lake (points G1–G10), as well as the junctures between the major lake and the Xinmiao Wetland (S4) and agricultural drainage ditches (S1–S3, S4). These sampling points were selected to study the spatial variations of water quality. Most of these sampling sites were accessed by boat, and the water samples were collected from May–September, 2018. During each field trip, 3000 mL of water was collected by a plexiglass sampler from the discrete sampling points. Their water quality parameters were either measured on-the-spot, or in our lab in Northeast Institute of Geography and Agroecology, where the samples were stored at 4 °C and then transferred to the lab. Surface water samples from points 1–18 and S1–S5 were collected on a monthly basis from May–September 2018, but the groundwater samples were only collected from G1–G10 in August 2018. Hence, in total 115 surface water samplings and 10 groundwater samplings were collected. Analytical data from these samples, together with some historical water quality data (up to 2017) from our previous research were used in the statistical analyses and evaluations of the eutrophication indices.

2.3. Water Sample Analysis

All water samples were analyzed for concentrations of TP, TN, ammoniac nitrogen (NH_3–N), chemical oxygen demand (COD) and chlorophyll a (Chl-a). NH_3–N and TP were measured using a Nessler's reagent spectrophotometry (HJ 535–2009) and molybdate spectrophotometry (GB/T 11893–1989), respectively. TN was analyzed using ultraviolet spectroscopy method (HJ 636–2012) after digestion by alkaline potassium persulfate. Chl-a was measured using a visible light spectrophotometer (HJ 897–2017). Numerous physical water quality parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), and water temperature (T_w), were measured by a Hanna measurement probe on-the-spot, during the sampling. Then, groundwater samples were analyzed for F^-, Cl^-, $SO_4{}^{2-}$, $CO_3{}^{2-}$, $HCO_3{}^-$, Mg^{2+}, Na^+, Ca^{2+}, and K^+ concentration using Ion Chromatograph (HJ 84–2016) and ICP MS (PE-NexION).

2.4. Calculations of Eutrophication Indices

The eutrophication indices were estimated by standard values, a comprehensive TLI ($\sum$) [30,31], or a logarithmic power function (eutrophication index: EI) [38,40]. The standard values of TN, TP, Chl-a, TLI, TSI, and EI are given in Table 1.

Table 1. The standard values of total nitrogen (TN), total phosphorus (TP), chlorophyll a (Chl-a), trophic level index (TLI), and eutrophication index (EI).

Grades	TN mg/L	TP μg/L	Chl-a μg/L	TLI	TSI	EI
Oligotrophic	0.08	<12	<7.3	<30	<40	<20
Mesotrophic	0.31	12–24	2.6–7.3	30–50	40–50	20–39.42
Eutrophic	1.2	24–96	7.3–56	50–60	50–70	39.42–61.29
Hyper eutrophic	2.3	96–192	56–155	60–70	70–80	61.29–76.28
Extreme eutrophication	9.1	192–384	>155	>70	>80	76.28–99.77

$$\mathrm{TLI}\left(\sum\right) = \sum_{j=1}^{m} W_j \times \mathrm{TLI}\,(j) \tag{1}$$

where W_j is correlative weight for trophic level index of j. TLI (j) is the trophic level index of j. TLI ($\sum$) is the comprehensive eutrophication index. W_j of Chl-a, TP, TN, and COD is 0.2663, 0.1879, 0.1790, and 0.1834, respectively. The unit of Chl-a, TP, TN, SD, and COD is μg/L, mg/L, mg/L, m, and mg/L, respectively.

$$\mathrm{TLI\ (Chl\text{-}a)} = 10\ [2.5 + 1.086\ln(\mathrm{Chla})] \tag{2}$$

$$\mathrm{TLI\ (TP)} = 10\ [9.436 + 1.624\ln(\mathrm{TP})] \tag{3}$$

$$\mathrm{TLI\ (TN)} = 10\ [5.453 + 1.694\ln(\mathrm{TN})] \tag{4}$$

$$\mathrm{TLI\ (SD)} = 10\ [5.118 - 1.94\ln(\mathrm{SD})] \tag{5}$$

$$\mathrm{TLI\ (COD)} = 10\ [0.109 + 2.661\ln(\mathrm{COD})] \tag{6}$$

The EI values, widely used for lakes in China [38,40] were calculated according to Equation (7).

$$EI = \sum_{j=1}^{n} W_j \times EI_j = 10.77 \times \sum_{j=1}^{n} W_j \times \left(lnX_j\right)^{1.1826} \quad (7)$$

where W_j and j are the same parameters used in Equation (1) and X_j is the code value of the j index, which was computed using the method stated by Li et al. [40]. The TLI and EI were widely applied to the study of eutrophication in China [30,31]. Hence, these three eutrophication indicators could be more accurate to evaluate the eutrophication of the lake.

2.5. Statistical Analysis

All statistical analyses were performed with the SPSS statistical software (IBM Ver. 22.0). Significant differences among the water quality parameters in surface water were evaluated through the Pearson correlation analysis. The monthly and yearly variations of TN, TP, NH_4–N, and NO_3–N in the Chagan Lake, together with the characteristic values of TLI, TSI, and EI in different sampling sites, were analyzed with SigmaPlot 12.5. The TLI, TSI, and EI maps were constructed by the ArcGIS (Ver. 10.2) software, while the TN, TP, NH_4-N, NO_3-N, pH, and F^- maps were constructed using the inverse distance weighting method. Factor analysis, score, and drawing using a principal component analysis (PCA) method was performed using Origin (Ver. 9.4).

3. Results and Discussion

3.1. Hydro-Chemical Properties of the Lake Water

The hydro-chemical properties of the Chagan Lake, the Xinmiao wetland, and groundwater are $HCO_3 \cdot CO_3$-Na·Mg, $HCO_3 \cdot CO_3$-Na·K, and $HCO_3 \cdot CO_3$-Ca·Mg, respectively (Figure 2). The concentration of Mg^{2+} and Ca^{2+} in groundwater was higher than that of the surface water, whereas the concentration of Na^+ in the groundwater was lower. The major anions were HCO_3^- and CO_3^{2-}, which accounted for more than 80% (Figure 2). The ion chemistry of lake water and groundwater could be related to the geology of the area. Naturally, the Chagan Lake was surrounded by saline–alkali land with a high pH [41]. Alkalinity increases with an increase in the amount of HCO_3^- and CO_3^{2-} in the irrigation discharge flowing into the lake, which threatens the development and survival of fish.

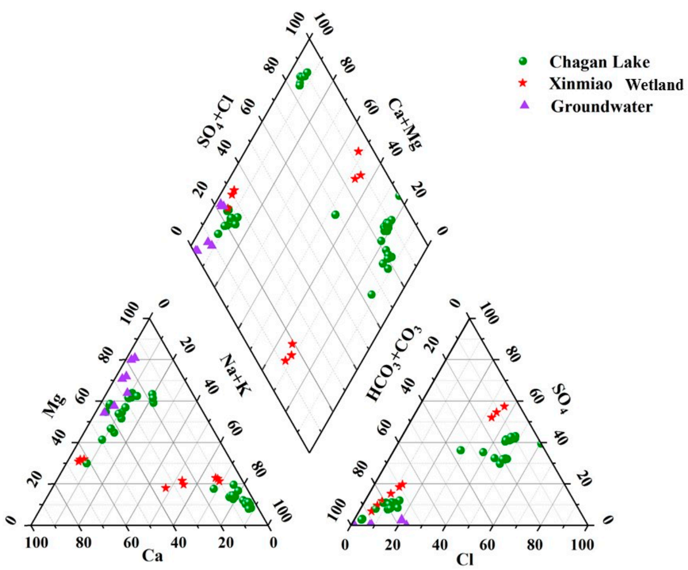

Figure 2. Piper diagram of the Chagan Lake in 2018.

Figure 3 gives the average values of three physical water quality parameters (EC, TDS, and T_w) at all 33 sampling sites. The average EC and TDS values of the lake water were generally higher than those of the groundwater (Figure 3 and Table 2). The values of all non-nutrient indicators largely varied across the seasons. In all 33 sampling sites, the seasonal variation of EC and TDS in site 4, 5, 10, 11, and 12 were different from the others sites, which showed the minimum value was in July (Figure 3A,B). In addition, these sites were adjacent to the fishery. The water temperature on the surface water of the major lake ranged 12.6 to 30.5 °C.

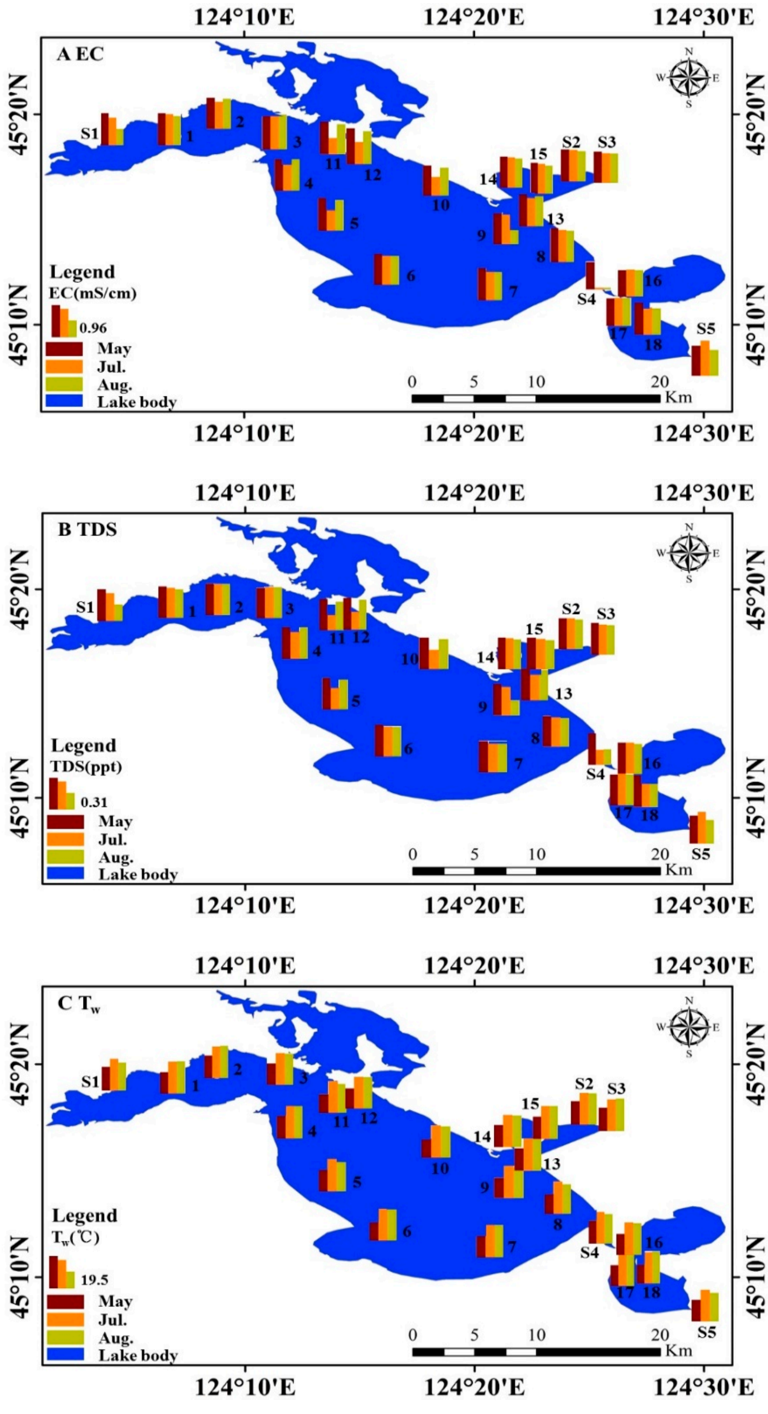

Figure 3. Spatial and monthly variations of electrical conductivity (EC) (**A**), total dissolved solid (TDS) (**B**), and T_W (**C**) water temperature of the surface water.

Table 2. The EC, TDS, and water temperature (T_W) values of groundwater around the lake.

	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10
EC (ms/cm)	0.65	1.07	0.64	1.8	0.5	0.43	0.45	0.70	0.65	0.83
TDS (ppt)	0.33	0.55	0.33	1.39	0.25	0.21	0.23	0.35	0.32	0.42
T_W (°C)	12.9	11.3	14.2	13.3	11.1	12.5	13.4	20.4	13.0	12.5

3.2. Temporal and Spatial Variation of N and P Concentrations

3.2.1. Monthly Variations

As shown in Figure 4, TN and TP concentrations in the lake water varied considerably with time, during the site investigation period of this study (i.e., May–September 2018) in different regions. Seasonally, the lowest monthly nutrient levels in the overall lakes were 0.85 mg/L (TN) and 0.04 mg/L (TP) in May, whereas the highest was 2.19 mg/L (TN) and 0.49 mg/L (TP) in August. Overall, the water quality (in terms of nutrient enrichment) deteriorated from May to August during the site investigation of this study. According to the water quality classification standards used in China, the overall water quality of the lake was Class IV or V during most of the unfrozen period in 2018 (Table 3), considerably below the recommended standards (Class II or III) for the major economic activity of this lake (i.e., fishing). In summer, more nutrients were carried into the Chagan Lake, with a heavier precipitation.

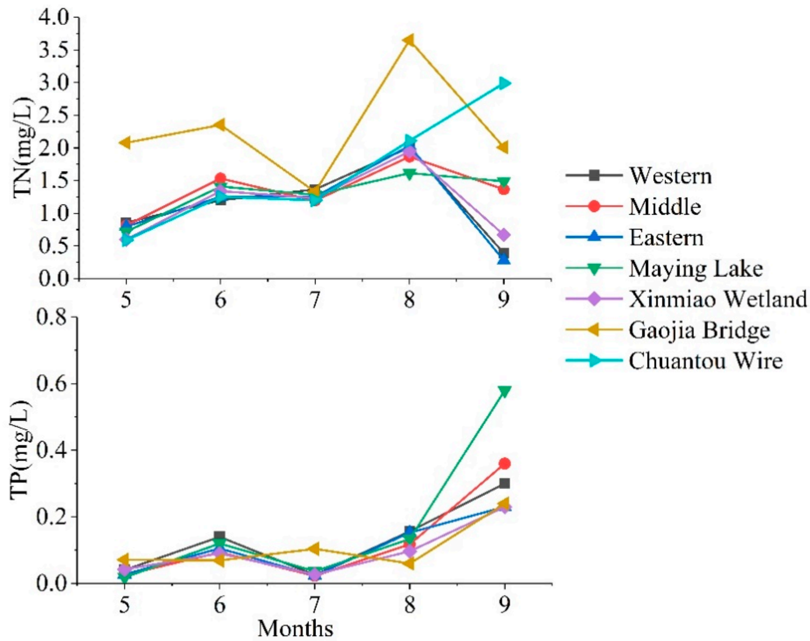

Figure 4. Monthly variations of TN and TP of different regions between May and September, in 2018.

Table 3. Chagan Lake water quality in 2018.

	May	June	July	August	September
TN	III	IV	IV	V	IV
TP	III	V	IV	V	V

Based on the average lunar nutrient levels in different regions, the TN and TP values of groups varied over a huge range (Figure 4). The highest values of TN and TP were in the western region and in the Maying Lake, respectively. Gaojia Bridge was the inlet of irrigation drainage flowing into the wetland. Chuantou Wire was the outlet of irrigation drainage outflow from the wetland. The purification effect of TN concentration was better than those of the TP concentration in the Xinmiao Wetland (Figure 4).

3.2.2. Variations of TN and TP in Different Locations

Figure 5 illustrates the variations of TN and TP concentrations in water at different locations of the lake. Generally, higher TN and TP concentrations were found in the northern and western sections of the lake, where drainage from the Da'an and Qianguo irrigation areas (Figure 1) entered into the lake via sampling points S1 and S4. This result confirmed a frequently expressed view that farmland drainage is an important source of N and P [42].

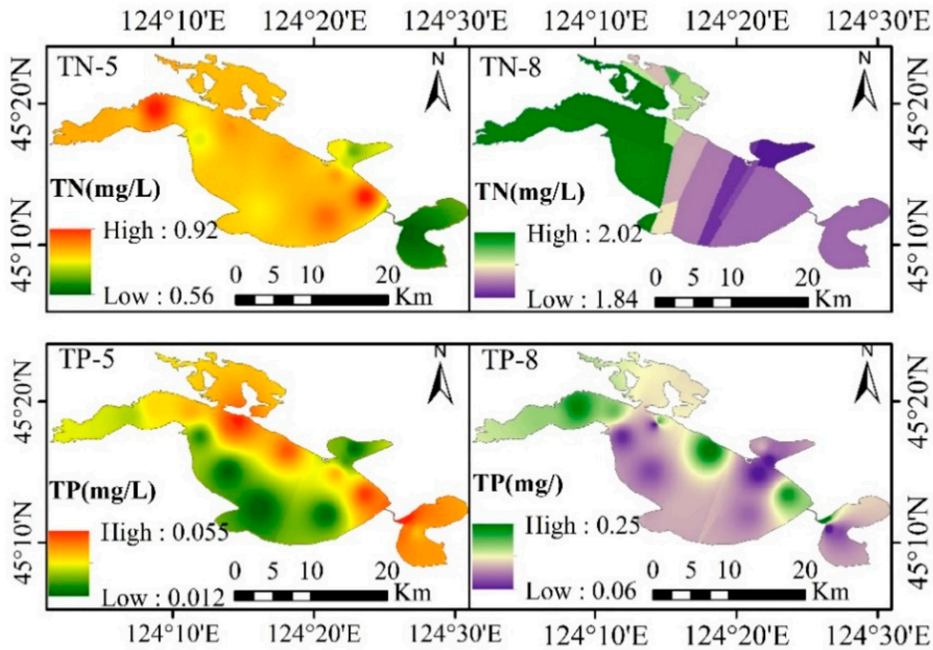

Figure 5. The spatial variation of TN and TP of the Chagan Lake in May and August of 2018.

At the southern end of the Chagan Lake, farmland drainage (the Qianguo irrigation area, Figure 1) flowed into the lake via the Xinmiao wetland. However, the concentration of TN in the Xinmiao wetland was generally lower than those in the Chagan Lake. These studies indicated that (a) water entering via the Xinmiao wetland was in fact diluting the nutrient levels in the lake, and (b) Xinmiao wetland played a water purification role. Wetlands can effectively decrease nitrogen and phosphorus of the irrigation discharge [43]. However, there was a significant removal efficiency of nitrogen and phosphorus between different plants [44]. Relative to its capacity of reducing the nitrogen load, the Xinmiao wetland showed a lower capacity for removing phosphorus from the drainage (Figure 4).

The high concentration of TN and TP in the western region (Figure 5) of the lake might also have been due to the fish farming activities, as organics and nutrients in fish feeds cause water quality deterioration via the food web [45]. In the meantime, the enrichment of nutrients result in the growth of algae, which affects the survival of fish [46]. Thus, excess nutrients can kill fish. The concentration of TP at sampling points 18 and S5 (Figure 1) were higher than those at points 11, 12, and S1, but there were no noticeable variations in the Xinmiao wetland.

Phosphorus and nitrogen released from the sediment was also a potential source for lake eutrophication (Figure 6) [47,48]. Due to restricted resources, this study did not include sampling and analysis of sediments. Thus, our methods neglect sediment and nutrient movements with groundwater–lake water interchanges. Nevertheless, the data still indicate that having a wetland system connect to a lake is beneficial, as it possibly acts as a buffer for nutrient input into the lake [49,50]. Preliminary mass balance of the wetland has been carried out by our group in a previous study [51]. The Xinmiao wetland also plays a role in purifying irrigation drainage from the Qianguo irrigation area. Hence, we suggest that a shallow constructed wetland is built between the western region of the lake and drainage from the Da'an irrigation area in the future.

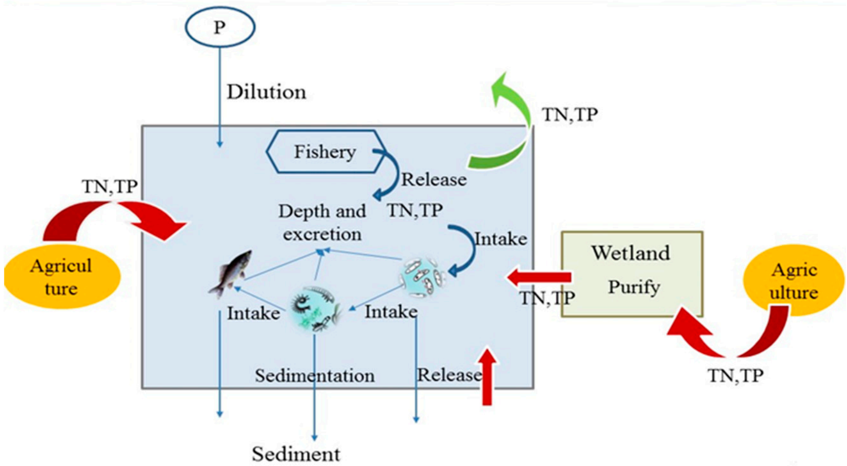

Figure 6. The conceptual graph for the source of TN and TP in the Chagan Lake.

3.2.3. Variations of pH, F^-, and Dissolved Oxygen in Different Locations

The pH, F^-, and dissolved oxygen (DO) is all the non-nutrient effects on fisheries [52–55]. The pH of all water samples were found to be greater than 8.0, and the water in the Chagan Lake was more alkaline than the Xinmiao wetland (Figure 7). The concentration of F^- ranged between 0.38 and 1.46 mg/L, averaging 0.99 mg/L (RMSE = 0.5487), which was considerably higher than the grade III water quality benchmark for F^- in the Chagan Lake. The F^- concentration in the groundwater ranged between 0.63 mg/L to 2.51 mg/L, with an average of 1.75 mg/L (RMSE = 0.5442). There was a high fluoride ion concentration because of the geological characteristics of this area. A high concentration of fluoride ion could permeate from groundwater into the lake through osmosis, which would lead to fish distortion and death [52,53]. DO ranged from 5.6 mg/L to 8.87 mg/L and the average value was excess 2 mg/L, in which the DO was not the major limiting factor for fish in the Chagan Lake.

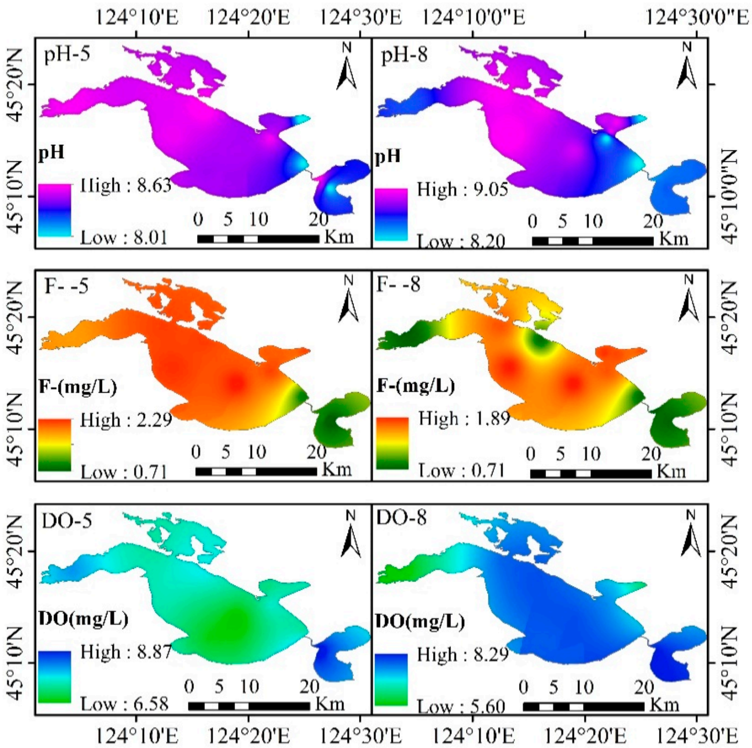

Figure 7. Spatial variations of pH, F^-, and dissolved oxygen (DO) in the Chagan Lake between May and August, 2018.

Figure 2 illustrates that the Chagan Lake was $HCO_3{}^{+}CO_3$-Na type water, whereas groundwater was $HCO_3{}^{+}CO_3$-Ca type. Controlling the drainage to the groundwater in the vicinity of the lake could be the second tool (in addition to building constructed wetland) to protect water quality, if this could be established and managed. It has been reported that a higher pH, EC, and TDS caused by the lake–groundwater exchange could decrease the concentration of F^- in lake water and help F^- immobilization in sediment [56–59], which would be desirable in summer fish farming season. In addition, a higher pH facilitates the immobilization of metal cations and desorption of anions [60].

3.3. Eutrophication Indices

The Trophic Level Index (TLI), Trophic State Index (TSI) and Eutrophication index (EI) are presented in Figure 8. The average values of TLI, TSI, and EI were 43.5, 44.8, and 47.0, respectively, in May, and 60.1, 63.0, and 66.6 in August, respectively. The TLI, TSI, and EI in August were higher than those in May, and EI > TSI > TLI in any month. Values of TLI and TSI indicated mesotrophic water in most parts of the lake (except at locations S1 and S5) in May. The values of EI indicated eutrophic conditions at any sites in May. Values of TLI, TSI, and EI were in a hyper eutrophic, eutrophic, and hyper eutrophic state in August, respectively. In total, water quality of the Chagan Lake was mesotrophic in May and was hyper eutrophic in August. High temperature and prolonged sunlight increased the risk of algal bloom [61], which was more likely to occur in the Chagan Lake in August.

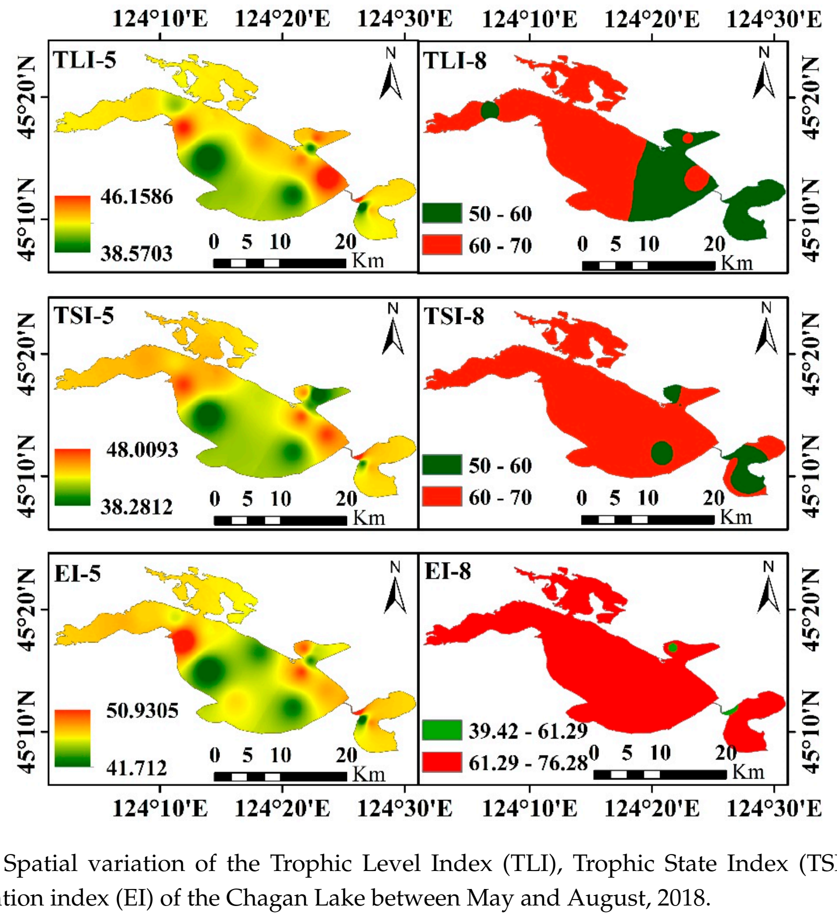

Figure 8. Spatial variation of the Trophic Level Index (TLI), Trophic State Index (TSI), and the Eutrophication index (EI) of the Chagan Lake between May and August, 2018.

The water quality in the Xinmiao wetland was clearly superior in the Chagan Lake, especially in August (Figure 8). The spatial variations of TLI, TSI, and EI in May were similar to those in August (Figure 8), while the values of TLI, TSI, and EI in August were generally higher. Eutrophication levels of the Chagan Lake were hyper-eutrophic in summer (Figure 8), in which the values excessed the 60. Irrigation drainage was also the major pollution source, especially as the lake was surrounded by the saline and alkaline land [62,63]. There was a certain purification effect, which showed that the eutrophication index (TLI, TSI) of the Xinmiao Wetland was lower than that of the Chagan Lake (Figure 8). The values of EI were higher than those of TLI and TSI, while the TLI and TSI could better describe the purification effect of the wetland.

Temperature is considered to be one of the primary factors determining the seasonal dynamics of eutrophication level [64]. It was pointed out that in winter, with decreasing temperatures, the dominance of the algae showed an obvious decrease. Overall, this map provides a basis for water quality management.

3.4. Statistical Analysis Results

The results of a Pearson correlation between TP, TN, NH_4-N, nitrate nitrogen (NO_3-N), chemical oxygen demand (COD_{mn}), Chla, SD, pH, EC, TDS, F^-, water temperature (T_w), biochemical oxygen demand (BOD), P, E, T, and relative humidity (Rh) are shown in Table 4. COD_{mn}, Chl-a, and BOD_5 were strongly positively correlated with TP and TN ($p < 0.01$), which showed that the organic contaminants such as bait was the major pollution source [65]. The concentration of F^- would be increased with the pH, EC, and TDS ($p < 0.01$), while the pH must be more than 7 [53]. There was a positive correlation between pH and F^- ($R^2 = 0.37$, $p < 0.01$); as shown in Table 4. However, the pH increased from May to August and F^- decreased from May to August (Figure 6). We know that the pH is not the major limiting factor for F^- in the Chagan Lake. Most lake eutrophication were affected by the precipitation and evaporation, while the major meteorological elements of the Chagan Lake were evaporation, which was different from low latitude lakes such as the Dianchi [37,66–68].

Principal component analysis (PCA) is a reduction dimensional statistical procedure that converts a set of correlated variables into a set of uncorrelated variables called principal components [69]. PCA is closely related to factor analysis, which typically incorporates more domain specific assumptions about the underlying structure and solves the eigenvectors of a slightly different matrix [67]. In our study, two PCA factors were extracted using all 14 water parameters and four meteorological parameters; the absolute percentages of variance were 47.0% and 46.1% in the dry and wet seasons, respectively (Figure 9A,C). Distribution of the sampling sites using the two factors' score are illustrated in Figure 9B,D, and there was a significant difference between the Chagan Lake and the Xinmiao Lake in spring. As shown in Figure 9A,B, the EC, TDS, and F^- were strongly positively correlated with PCA2, and the pH and BOD_5 were strongly negatively and positively correlated with PCA1 in spring. The import and export of the lake were positively correlated with PCA1. Special sites were located at the Xinmiao wetland, which was strongly negatively correlated with PCA2. Therefore, EC, TDS, F^-, NH_4-N, and BOD were the major factors affecting the Chagan Lake in spring. N transportation and transformation were quite different between the farmland drainage and groundwater due to distinctive biochemical processes and hydrological regimes [70]. Site S4 was the connection between the wetland and the lake, which might be subjected to the stress of residents' living, groundwater, and sediment release. It showed that salinity appears to exert a major control on the nitrogen cycle at this site [71]. TP and NO_3-N were strongly positively correlated with PCA2 in summer. Special sites were S5, 1, and 6 in summer. From Figure 9C,D, it seemed that NO_3-N and TP were the major factors affecting S5, and TN was the major factor affecting site 1, which was similar to the results shown in Figure 4. Nitrogen and phosphorus carried from farmland drainage was the major pollution source for lakes [72]. Therefore, N of S5 was from the Qianguo irrigation district and the P of site 1 was from the Da'an irrigation district. The water quality was an obvious difference in the western region and the Xinmiao Wetland in spring (Figure 9B). The water quality was poor in summer. These results are similar to those shown in Figures 5 and 8. F^- and pH were the major non-nutrient factors in spring, and TN and TP were the major nutrient factors in summer (Figure 9A,C).

Table 4. The Pearson correlation between TP, TN, NH_4-N, NO_3-N, COD_{mn}, Chl-a, SD, pH, EC, TDS, F^-, T_w, DO, BOD, P, E, T, and Rh.

	TP	**TN**	**NH_4-N**	**NO_3-N**	**COD_{mn}**	**Chla**	**SD**	**pH**	**EC**	**TDS**	**T_w**	**F^-**	**DO**	**BOD_5**	**P**	**E**	**T**	**Rh**
TP	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TN	0.43 **	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NH_4-N	0.31 *	0.26	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NO_3-N	0.25	0.88 **	0.04	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
COD_{mn}	0.48 **	0.63 **	0.12	0.59 **	1	-	-	-	-	-	-	-	-	-	-	-	-	-
Chla	0.43 **	0.64 **	0.17	0.53 **	0.46 **	1	-	-	-	-	-	-	-	-	-	-	-	-
SD	−0.06	0.27	−0.01	0.39 **	0.09	−0.06	1	-	-	-	-	-	-	-	-	-	-	-
pH	0.05	0.19	−0.24	0.38 **	0.32 *	−0.13	0.10	1	-	-	-	-	-	-	-	-	-	-
EC	−0.17	−0.41 **	−0.01	−0.36 *	−0.22	−0.37 *	0.01	0.33 **	1	-	-	-	-	-	-	-	-	-
TDS	−0.18	−0.41 **	−0.02	−0.35 **	−0.22	−0.37 *	0.02	0.33 **	0.99 **	1	-	-	-	-	-	-	-	-
T_w	0.34 *	0.72 **	0.34 *	0.70 **	0.64 **	0.35 *	0.03	0.54 **	−0.07	-0.07	1	-	-	-	-	-	-	-
F^-	−0.28	−0.50 **	−0.07	−0.44 **	−0.24	−0.45 **	0.01	0.37 **	0.90 **	0.89 **	-0.17	1	-	-	-	-	-	-
DO	0.20	0.34 *	0.07	0.29	0.52 **	0.24	−0.14	0.57 **	0.21	0.20	0.62 **	0.12	1	-	-	-	-	-
BOD_5	0.72 **	0.74 **	0.75 **	0.44 **	0.54 **	0.51 **	0.14	-0.17	−0.16	−0.16	0.62 **	−0.28	0.27	1	-	-	-	-
P	0.14	0.05	0.20	0.06	0.13	0.16	−0.01	-0.20	−0.14	−0.13	0.04	−0.12	−0.10	0.36 *	1	-	-	-
E	−0.03	0.34 *	0.03	0.25	0.27	0.25	−0.07	-0.04	−0.31 *	−0.32 *	0.33 *	−0.33 *	0.25	0.12	−0.09	1	-	-
T	0.28	0.41 **	0.22	0.40 **	0.46 **	0.31 *	0.09	0.45 **	0.08	0.08	0.59 **	−0.06	0.47 **	0.36 *	−0.11	0.21	1	-
Rh	0.30 *	0.61 **	0.19	0.61 **	0.60 **	0.38 **	0.02	0.27	−0.25	−0.24	0.65 **	−0.35 *	0.29	0.43 *	0.43 *	0.14	0.46 **	1

Note: ** indicates the 0.01 significance test and * indicates the 0.05 significance test. Rh indicates the relative humidity.

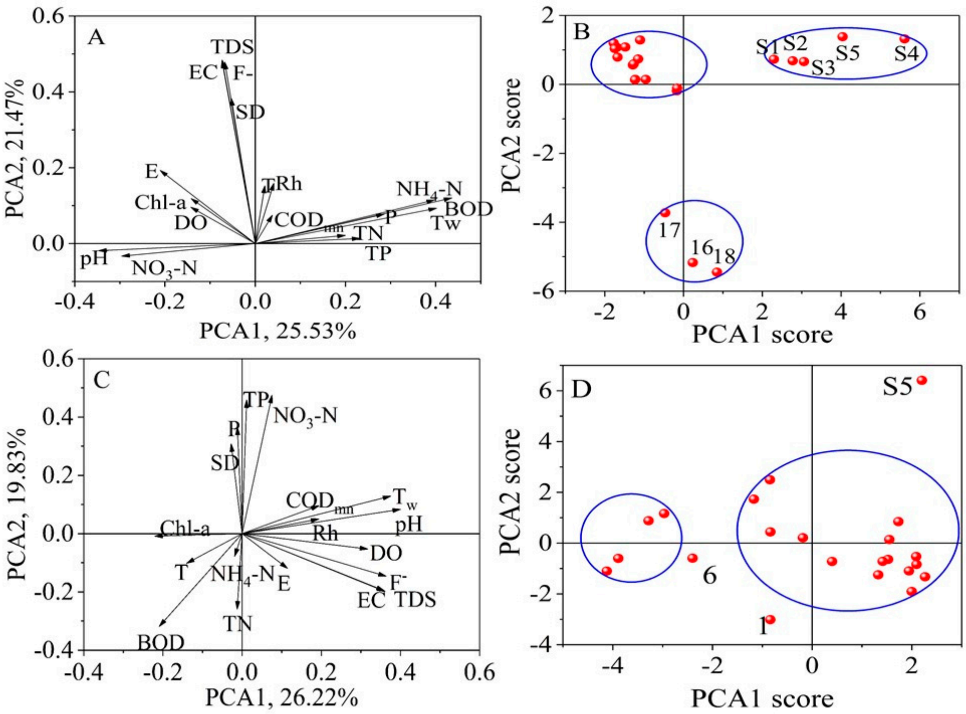

Figure 9. Principal component analysis based on the water variables in spring (**A**,**B**) and summer (**C**,**D**) seasons. Ellipses indicate the 95% confidence limit.

4. Conclusions

The study assessed the water quality and eutrophication risk of the lakes in the agriculture-stressed areas. High levels of TN and TP led to an obvious eutrophication of the lakes in summer, based on the results of this study. This study provided the spatial patterns of water quality parameters and eutrophication index in 2018. There was an obvious spatiotemporal heterogeneity of water quality parameters and eutrophication index. Seasonally, water quality was worse in the summer than in spring, with higher values of the eutrophication index being seen in summer. The lake was hypereutrophic in summer based on three types of eutrophication index. The values of EI were higher than those of TLI and TSI, while the TLI and TSI could better describe the purification effect of the wetlands. Spatially, the TN and TP concentration was higher in the Chagan Lake than those in the Xinmiao wetland, due to the purifying capacity of the wetland. At the same time, TN and TP concentrations were higher in the western region than those in the middle and eastern regions of the Chagan Lake, due to the irrigation discharge. The relationship analysis of the nutrient concentrations of TN and TP with Chl-a, COD_{mn}, and BOD_5 indicated that the changes in the TN and TP concentrations was directly related to the changes in Chl-a, COD_{mn}, and BOD_5 to some degree. In addition, the F^- concentration was the superior limiting factor of water quality parameter in the Chagan Lake. These results showed an obvious trophic state based on the statistical analysis, and irrigation discharge was found to be the major influencing factor for eutrophication. Such systematic research was necessary to derive a sustainable management of lake ecosystems.

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