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Article

Seasonal Stratification Characteristics of Vertical Profiles and Water Quality of Lake Lugu in Southwest China

Fengqin Chang [1], Pengfei Hou [1,*], Xinyu Wen [2], Lizeng Duan [1], Yang Zhang [1] and Hucai Zhang [1,*]

[1] Institute for Ecological Research and Pollution Control of Plateau Lakes, School of Ecology and Environmental Science, Yunnan University, Kunming 650500, China
[2] School of Geography and Engineering of Land Resources, Yuxi Normal University, Yuxi 653100, China
* Correspondence: houyu8806@163.com (P.H.); zhanghc@ynu.edu.cn (H.Z.)

Abstract: According to the vertical section monitoring data of Lake Lugu water temperature (WT), electrical conductivity (EC), dissolved oxygen (DO), pH and chlorophyll-*a* (Chl-*a*) parameters in January (winter), April (spring), July (summer), and October (autumn) in 2015, the vertical stratification structure of WT and the null seasonality of water chemistry were analyzed. The relationship between the seasonal variation of WT stratification and the spatial and temporal distribution of EC, pH, DO and Chl-*a* was explored. The relationship between EC and WT was found for the epilimnion, thermocline and hypolimnion. The results of the study showed that: (1) The Lake Lugu water body shows obvious thermal stratification in spring, summer and autumn. In winter, the WT is close to isothermal condition in the vertical direction; in summer, the thermocline is located at 10–25 m water depth; while in autumn, the thermocline moves down to 20–30 m. (2) The Hypolimnion WT was maintained at 9.5 °C~10 °C, which is consistent with the annual mean temperature of Lake Lugu, indicating that the hypolimnion water column is stable and relatively constant, and reflects the annual mean temperature of the lake. The thermally stratified structure has some influence on the changes of EC, DO, pH and Chl-*a*, resulting in the obvious stratification of EC, DO and pH in the water body. (3) Especially in summer, when the temperature increased, the thermal stratification phenomenon was significant, and DO and pH peaked in thermocline, with a decreasing trend from the peak upward and downward, and the hypolimnion was in an anoxic state and the pH value was small. Although chlorophyll a remained low below thermocline and was not high overall, there was a sudden increase in the surface layer, which should be highly warned to prevent a large algal bloom or even a localized outbreak in Lake Lugu. (4) There is a simple linear function between EC and WT in both vertical section and Epilimnion, thermocline and hypolimnion, which proves that Lake Lugu is still influenced by natural climate and maintains natural water state, and is a typical warm single mixed type of lake. (5) It is suggested to strengthen water quality monitoring, grasp its change pattern and influence factors, and take scientific measures to prevent huge pressure on the closed ecological environment of Lake Lugu, and provide scientific basis for the protection of high-quality freshwater lakes in the plateau.

Keywords: Lake Lugu; Yunnan; thermal stratification; seasonal changes; water quality

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1. Introduction

In the context of global change, the study of the mechanism of the effect of temperature increases and eutrophication on the thermal stratification of lakes and reservoirs and its ecological and environmental effects has become one of the most common problems in current international research [1,2]. Lake thermal stratification and thermal cycling are important factors governing various physicochemical processes (e.g., dissolved oxygen (DO) distribution, nutrient exchange, microbial activity [3], bottom sediment nutrient release, etc.) and kinetic phenomena such as upstream and downstream water mixing and convection, and are important indicators affecting lake biological production and ecosystem evolution [4,5]. In general, the vertical distribution of water temperature (WT) in lakes varies with the difference in depth of the lake. Compared with shallow lakes, deep-water lakes have large and long-lasting temperature gradients [6], and deep-water lakes are less affected by wind, have strong heat storage capacity, and have large vertical temperature differences, which make it easy to form stable stratification [7], so thermal stratification is a natural phenomenon that exists in deeper lakes (water depth > 10 m) [8]. The thermocline of deep-water lakes is like a blocking layer in which the vertical gradient of the physicochemical properties of the lake water is large, while the physicochemical properties of the lake water in the epilimnion and hypolimnion are more uniform, which is due to the existence of the thermocline that can effectively impede convection, turbulence and molecular exchange in the upper and lower water bodies, affecting the distribution of light and nutrients in the lake water column, thus influencing the vertical distribution of water chemistry parameters [9,10]. For deep-water lakes (including reservoirs) with great and continuous temperature differences, the vertical distribution and variation patterns of WT determine the vertical stratification and mixed exchange of chemical factors as well as biological factors (phytoplankton, animals, etc.), which in turn profoundly affect the lake ecosystem [11,12]. Therefore, to understand the significance of water chemistry parameters in deep-water lakes, it is necessary to conduct an in-depth study of seasonal thermal stratification in lakes [13].

With the frequent occurrence and increasing intensity of extreme climatic and meteorological events [14], a series of changes and responses will also occur in the climatic environment of the monsoon region, especially in the highly variable southwest (Indian) monsoon region, causing corresponding changes in lakes [15]. All these changes will lead to changes in the hydrological cycle and water resources, and will have a significant impact on our water resources not only in terms of quantity but also in terms of regional distribution [16–18]. This requires an understanding and knowledge of the basic characteristics of lakes. Several scholars have conducted in-depth and systematic studies on the seasonal stratification and water chemistry characteristics of many natural deep-water lakes, shallow lakes, and large artificial reservoirs [19,20]. These results indicate that parameters such as WT, DO, chlorophyll-*a* (Chl-*a*), pH, electrical conductivity (EC), cell density of cyanobacteria, and turbidity are prone to vertical seasonal stratification in summer, especially in deep-water lakes and reservoirs [21,22]; vertical changes in lake thermal stratification affect the upward and downward distribution of water chemistry parameters such as DO, pH, and Chl-*a*, and seasonal stratification of water chemistry parameters caused by changes in WT in a deep-water lake [23–25]. Lugu is a warm temperate semi-enclosed plateau deep-water lake, the lake water does not freeze throughout the year, and it is easy to form a stable thermal stratification phenomenon; and the influence of inflow and outflow on the heat balance of the lake is minimal, so it is the best choice to study the seasonal variation of lake water bodies. Zhao et al. [26] studied the stability, mixing depth, thermocline depth, and buoyancy frequency to determine the onset, development, and termination of seasonal temperature stratification. However, this study only sampled the northern part of the lake and did not discuss the relationship between conductivity and temperature difference. Wang et al. [27] analyzed the variation of DO concentration at the surface WT and bottom of Lake Lugu and concluded that Lake Lugu is a warm single mixed lake with higher DO in autumn and winter and the highest DO in the hyaline zone below the thermocline in summer and autumn. Chen et al. [28] used the DYRESM model to investigate the stratification and other thermodynamic conditions in Lake Lugu in southwest China. the understanding of the changes of water chemistry parameters such as lake temperature, Chl-*a*, and DO concentrations, and pH is not only of practical significance for lake eutrophication control and water quality protection, but also very important for local and even global climate change studies.

Lake Lugu, as an important deep-water lake in the southwest monsoon region, is relatively little understood by us, lacking detailed studies on its seasonal stratification of temperature and vertical variation of water chemistry parameters. Especially in recent years, more and more human traffic has not only changed the original production and living style of local residents, but also caused great pressure on the relatively closed ecological environment of Lake Lugu, which made the garbage around the lake piled up and sewage directly into the lake, polluting the local natural ecological environment. Based on this, the vertical stratification structure of WT and the spatial stratification of water chemistry were analyzed based on the vertical section monitoring data of Lake Lugu WT, EC, pH, DO, and Chl-*a* parameters in January (winter), April (spring), July (summer), and October (autumn) in 2015. The seasonal stratification characteristics and patterns of Lake Lugu WT were revealed. Epilimnion, thermocline, and hypolimnion as a function of EC and WT. The results of the study can help improve the health of lake ecosystems and provide a scientific basis for the conservation of high-quality freshwater lakes in the plateau.

2. Data and Methods

2.1. Background of Lake Lugu

Lake Lugu is located at the junction of two provinces, northwestern Yunnan Province and southwestern Sichuan Province, and is a plateau faulted solution trap lake (Figure 1). Its main fault structure system consists of one northwest–southeast and two east–west faults together [29]. The geographic coordinates of Lake Lugu are 27°41′ to 27°45′ N, 100°45′ to 100°51′ E. Lake Lugu is a natural freshwater lake belonging to the Jinsha River. It slightly trends from northwest to southeast, with a length of 9.5 km from north to south, a width of 5.2 km from east to west, and a coastline of about 44 km. According to data measured in 2005 [30], the lake is at an altitude of 2692.2 m, consists of an area of 57.7 km^2, has a maximum depth of 105.3 m, and an average depth of 38.4 m. The water storage capacity is 1.953 billion m^3. Its annual amount of water entering is 110 million m^3, maximum water transparency is 12–14 m, and the nutritional level of the water body is steadily maintained at a Class I water quality.

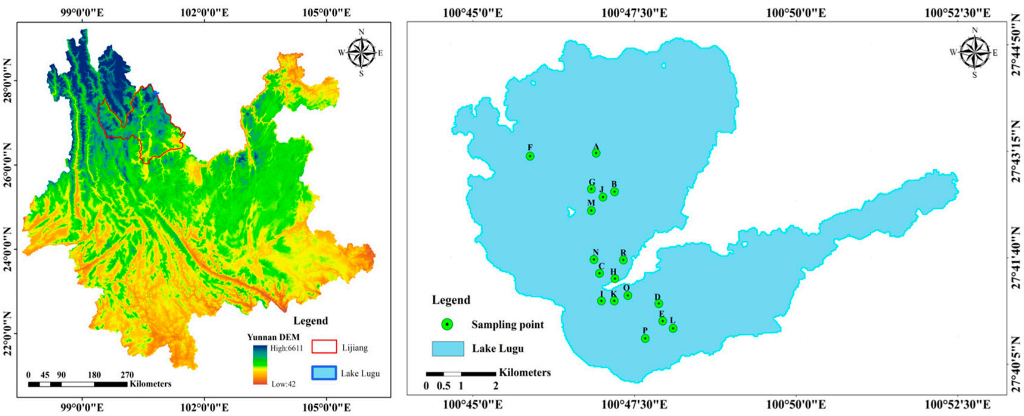

Figure 1. Distribution of monitoring and sampling sites in Lake Lugu.

Lake Lugu is located in the southwest monsoon climate zone, belongs to the subtropical highland monsoon climate zone, and is characterized by a warm, humid mountainous monsoon climate. It is controlled by dry continental winds in winter and humid Indian Ocean monsoon in summer, with distinct dry and wet seasons. The average annual rainfall is 730 to 830 mm, with 89% of the annual rainfall concentrated in the rainy season (June to October). Lake Lugu obtains its water supply primarily from precipitation, surface, and groundwater. The lake outlet is located on the eastern shore of the southern lake area, with the Caohai wetland being the only outlet. In the annual dry season (January to May), the lake has almost no outflow. The lake's water replacement duration is up to 18.9 years and it is a semi-closed lake [31,32].

2.2. Data Collection and Index Determination

Due to the large area of Lake Lugu and the influence of geological structure, the lake was divided into two parts: south and north. To improve the monitoring efficiency of the lake and assess the entire lake, monitoring sections were established in January, April, July, and October 2015 in the north and south regions of Lake Lugu (Figure 1). In January, the monitoring sections were marked as points A (100°46′28″ E~27°43′15″ N), B (100°46′33″ E~27°41′29″ N), C (100°46′33″ E~27°40′51″ N), D (100°46′47″ E~27°42′38″ N) and E (100°47′18″ E~27°41′00″ N); April as F (100°45′27.15″ E~27°43′13.34″ N), G (100°46′25.08″ E~27°42′42.39″ N), H (100°46′41.14″ E~27°40′57.72″ N) and I (100°46′40.71″ E ~27°41′20.48″ N); July as J (100°45′40.9″ E~27°43′7.2″ N), K (100°46′8.5″ E~26°42′43.4″ N), L (100°47′7.3″ E~27°41′0.8″ N) and R (100°48′6.3″ E~27°40′1.8″ N), and; M (100°46′24″ E~27°42′24″ N), N (100°46′28″ E~27°41′40″ N), O (100°46′57″ E~27°41′08″ N), P (100°47′13″ E~27°40′37″ N) in October. Sampling locations were established using the satellite-based Global Positioning System (GPS). Water quality parameters, including WT, DO, Chl-*a* concentration, pH value, and phycocyanin concentration, among others, were measured with a Xylem Analytics YSI-6600 multi-parameter sonde (Xylem, Milford, OH, USA). A vertical line was established at each site to monitor water quality at different depths. Data were first collected at 0.1–1 m below the water surface, and the last data were monitored 0.5 m above the lake bottom, with additional data collected at 1 m intervals. To ensure data accuracy, each depth was measured six times.

2.3. Analysizing Methods

2.3.1. Lake Quality Level

River water quality classification was based on the national quality standards (GB 3838-2002) [33]. According to the environmental functions and protection objectives of surface waters, the lake quality level was divided into the following five functional level categories (Table 1):

Table 1. Water function and standard classification.

Water Quality Classification	Scope of Application
Class I	Mainly applicable to source waters and national nature reserves.
Class II	Mainly applicable to centralized drinking water, surface water sources, first-class protected areas, etc.
Class III	Mainly applicable to secondary protection zones, fisheries, and swimming areas of centralized drinking water surface water sources.
Class IV	Mainly applicable to general industrial water use areas and recreational areas where the human body is not in direct contact with water.
Class V	Mainly applicable to agricultural water use areas and general landscape requirements.

2.3.2. Correlation Analysis Method

Pearson's correlation coefficient is a metric used to describe relationships among variables. This method uses the covariance matrix of data to evaluate the strength of the relationship between two vectors. Normally, the Pearson's correlation coefficient between two variables, β_i and β_j, can be calculated as shown in Equation, where $cov(\beta_i, \beta_j)$ is the covariance, $var(\beta_i)$ is the variance of β_i, and $var(\beta_j)$ is the variance of β_j [34].

$$R(\beta_i, \beta_j) = \frac{cov(\beta_i, \beta_j)}{\sqrt{var(\beta_i) \times var(\beta_j)}} \quad (1)$$

3. Results and Discussion

3.1. Subsection Vertical Stratification and Seasonal Temperature Fluctuations

Under normal circumstances, the WT of deep-water plateau lakes reacts sensitively to changes in seasonal temperature [35]. Thus, in summer, thermal stratification of the body of water results in changes in the lake's WT. The isothermal layer gradually decreases with increasing depth, resulting in a sharp drop in the thermocline. Similar to other deep-water lakes on the plateau (alpine), the WT of Lake Lugu has distinct stratification and mixing features in the vertical section during spring, summer, autumn and winter. The vertical distribution of WT in January (winter), April (spring), July (summer), and October (autumn) at each sampling site in Lugu Lake (Figure 2) clearly shows that the WT in Lake Lugu varies seasonally, with a significant temperature gradient of the water column in the vertical section in April, July, and October, and a gradual change in the depth in the thermocline. In April, July, and October, the temperature gradient in the vertical section of the water column were obvious, and the depth of the thermocline changed gradually with time, but in January, as the temperature decreased, the overall temperature of the water column also decreased, showing no temperature gradient in the vertical section.

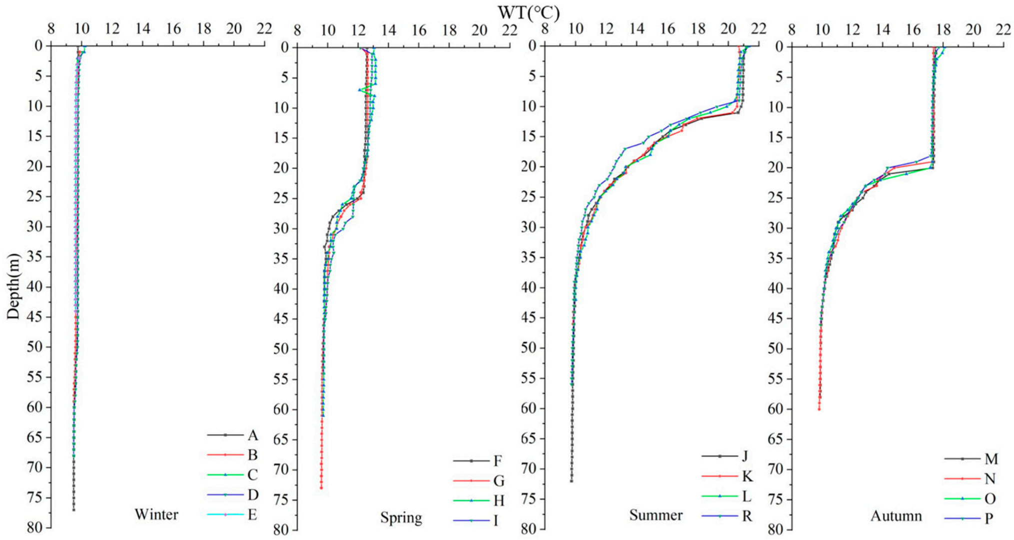

Figure 2. Seasonal variations of vertical water temperature (WT) section in Lake Lugu.

In April, with an increase in solar radiation and temperature, the surface water body rapidly warmed up, causing a gradual increase in temperature difference between the deep-water body and the appearance of the stratification phenomenon. The temperature of Lake Lugu reached its maximum in July, which made the external heat transfer from the surface layer to be continuously downward, decreased the maximum temperature difference, and shifted the depth of the thermocline upward, leading to an obvious temperature stratification phenomenon. According to the thermocline definition, which suggests a water layer having a WT gradient > 0.2 °C/m [36,37], Lake Lugu's WT in July could be divided into three layers in a vertical section: epilimnion (0–10 m), thermocline (11–25 m), hypolimnion (<25 m). As the temperature dropped in October, the depth of the thermocline decreased to a 20 m water level. In general, reservoirs with a depth of ≥7 m have a thermocline, which causes lakes' WT to drop by more than 1 °C with every 1 m drop in water depth. The distribution of WT in a layered lake reservoir, formation of thermocline or the up-and-down exchange of water has significant effects on the vertical distribution of DO, distribution of nutrients, and distribution of aquatic organisms, especially phytoplankton. With weak solar radiation and low temperature in January, the lake water bodies release latent heat, eventually forming a uniform temperature distribution above and below the water body without obvious stratification. During seasonal scale change, the position of the thermocline constantly shifted downward due to turbulence, convection, and the molecular diffusion of the lake water after its formation. Therefore, the position of the thermocline in Lake Lugu was about 15 m and 10 m lower in spring and autumn than in summer and disappeared completely in winter.

The WT in the surface layer of Lake Lugu was influenced by external climatic factors and varied significantly in July and October, ranging from 17.1 °C to 22 °C. However, the deep-water layer (less than 40 m) ranged between 9.5 °C to 10 °C, which was constant throughout the year. According to three weather stations near Lake Lugu, Yanyuan (27.27° N, 101.37° E; 2439.4 m), Zhongdian (27.50° N, 99.42° E; 3276.1 m), and Muli (28.08° N, 100.50° E; 2666.6 m), the annual average temperature of Lake Lugu is 10.3 °C. The mean temperature of the water from 1951 to 1980 was 12.6 °C, 5.4 °C, and 11.5 °C, respectively, and after correction, the annual average temperature layer of Lake Lugu and the surrounding lake area was basically consistent, indicating that the water in the mean temperature layer of Lake Lugu has been at a constant temperature for many years, reflecting the mean annual temperature of the lake area.

From a spatial point of view, the surface WT in the northern part of Lake Lugu was lower than in the southern part of the investigated year. In spring, summer, and autumn, there was thermal stratification in the water body north of Lake Lugu, especially in summer and autumn, and the WT had a variable temperature layer, thermocline layer, uniform temperature layer in the vertical section. In April, the thermocline appeared in the northern water body when the water layer was 25 m and re-appeared in the southern water body when the water layer was 21 m. In July, the thermocline of the north and south water bodies appeared at the water layer at 10 m, and in late October, the thermocline appeared in both the northern and southern water bodies at the 20 m water layer. The warming and cooling of the surface WT in the northern water column were slower than those in the south due to the difference in water depth or wind effects in the same lake, resulting in differences in the horizontal distribution of WT.

3.2. Vertical Variation Characteristics and Seasonal Dynamics of Hydrochemical Parameters

3.2.1. Electrical Conductivity (EC)

Electrical conductivity is a measure of the ability of a substance to carry an electrical current and is influenced by factors such as salinity, dissolved solids in water, temperature, and water supply. Since the EC of water is affected by WT, nutrients, and water supply, seasonal stratification led to evident EC changes (Figure 3), with the vertical distribution trend of water EC in Lake Lugu consistent with WT. Figure 3 shows a small variation in EC in January, maximum EC in July, and minimum EC in April. The EC of Lake Lugu changed significantly on the vertical section, first showing a decreasing trend and then remaining constant. The EC changed slightly in the thermotropic and hypolimnion layers but significantly changed in different months.

The trend was consistent with the vertical variation of WT in January, and there was no significant difference in conductivity except for a very slight increase in the water layer below 49 m. However, EC varied vertically in April, July, and October, resulting in obvious stratification. Among them, EC changed abruptly at a water layer of 25 m in April and stabilized below 31 m. In April, July, and October, EC varied vertically and was stratified. In April, EC changed abruptly at 25 m and stabilized below 31 m. In July, EC fluctuated from 10 to 25 m and stabilized below 25 m. In October, EC changed abruptly at 20 m and stabilized above this depth, decreased below 20 m to 30 m, and stabilized below 30 m. In October, the EC changed abruptly at 20 m and stabilized above this depth. According to the measurement results in 2015, the spatial difference in water conductivity in the northern and southern parts of Lake Lugu was not large, with a very similar vertical change trend. From a seasonal point of view, with the same trend of change in spring, summer and autumn, EC changed significantly, peaked in summer and autumn, and was lowest in winter.

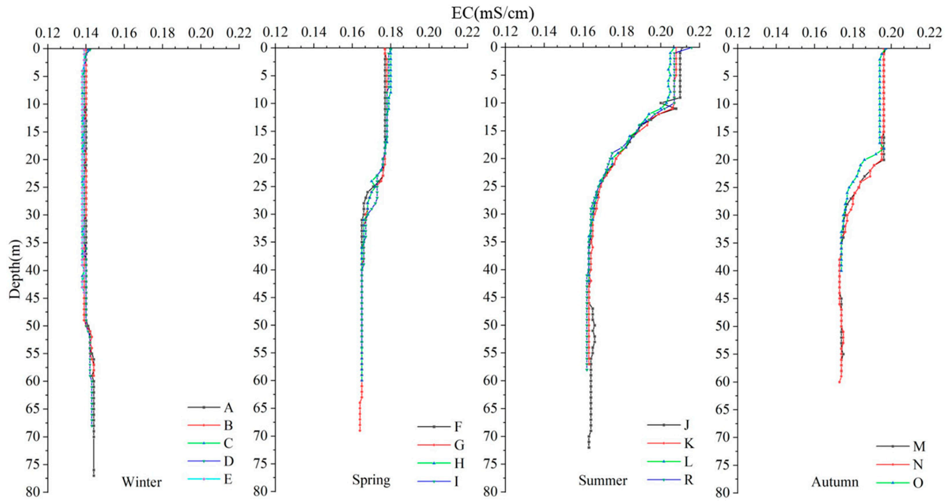

Figure 3. Seasonal variations of vertical electrical conductivity (EC) in Lake Lugu.

3.2.2. Dissolved Oxygen (DO)

With the trend of changes in WT, the vertical distribution of DO in the water body of Lake Lugu demonstrated a clear seasonal stratification (Figure 4). Based on the measured data, the DO concentration in the surface layer of Lake Lugu in January, April, July, and October was almost unchanged from 6.5 to 8.5 mg/L, but the vertical changes were significantly different. In January, the DO of the water body did not change significantly within 48 m of the vertical section, with a mass concentration of 7.0 to 8.5 mg/L. The DO of the water body with a large water depth in the north changed suddenly at 50 m, and the DO of the water layer below 55 m was <4.0 mg/L. However, when the water depth exceeded 60 m, the DO was <2.0 mg/L, forming an anaerobic environment. As of April, the mass concentration of DO increase was due to the formation of the recessive layer in the lake. We observed that DO was stabilized at about 8.0 mg/L above the 25 m depth. When the water depth increased, DO gradually decreased to 5.5 mg/L. The change in DO in July was more complex and diverse, and the vertical distribution of DO in the changed temperature layer corresponding to 0~10 m was relatively stable. DO gradually increased downward from the depth of 11 m and reached its maximum value at the 20 m depth, forming a high DO layer in the 11~33 m section. In October, DO was evenly distributed vertically in the upper layer of the water at 0~21 m, with a value slightly higher than 7.0 mg/L. At 21 to 45 m depths, the DO concentration dropped sharply and was 2.0 to 3.0 mg/L at depths below 45 m.

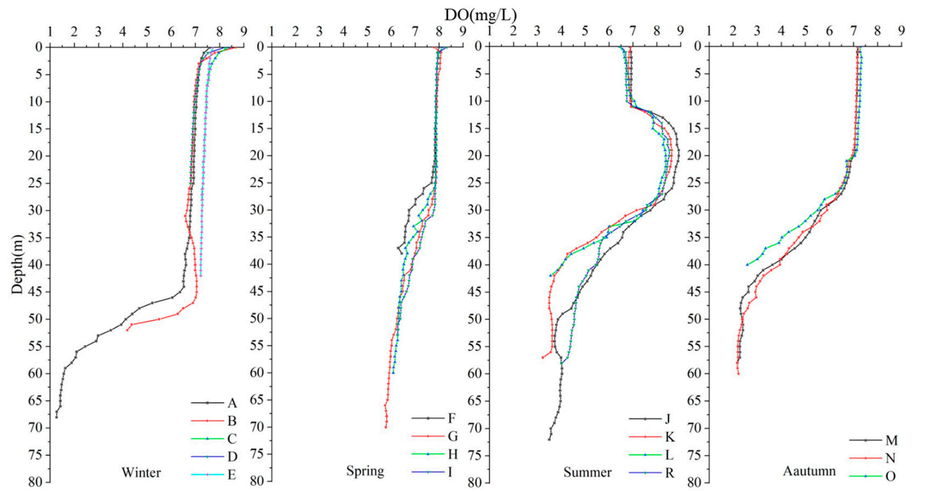

Figure 4. Seasonal variations of vertical dissolved oxygen (DO) section in Lake Lugu.

3.2.3. pH Value

The pH value of the Lake Lugu water body was generally slightly alkaline, and there was a clear stratification with obvious vertical and seasonal variations (Figure 5). Due to the high light intensity at the surface, many aquatic organisms thrived, photosynthesis was strong, and a large amount of CO_2 was consumed, resulting in a high surface water pH value. The photosynthesis of aquatic plants in deeper water was weak, and the decomposition of organic matter led to CO_2 and organic acids accumulation in the water. At the same time, due to the long retention time of the lower water and the slow molecular diffusion rate, the pH value decreased slowly. Thus, except in summer, the vertical change in pH value in Lake Lugu gradually decreased.

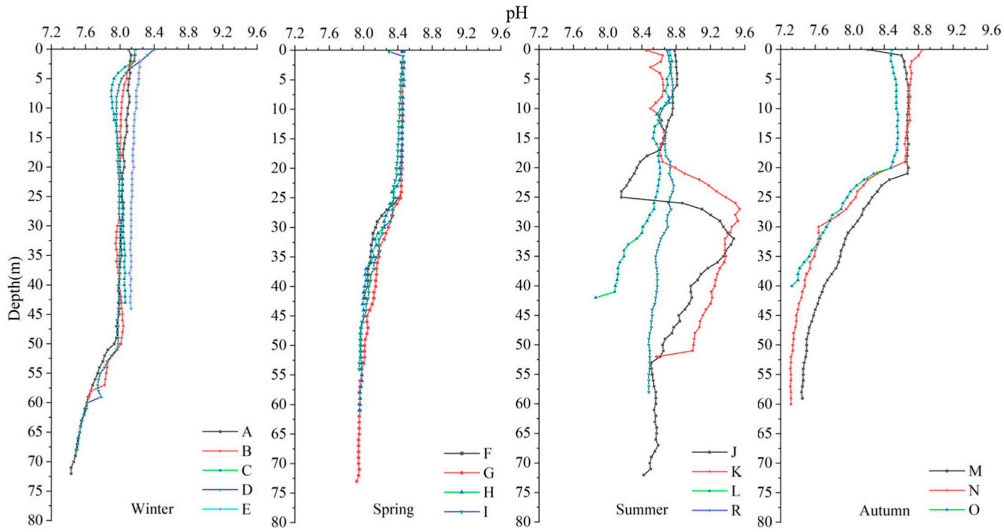

Figure 5. Seasonal variations of vertical pH section in Lake Lugu.

The vertical variation of pH value (Figure 5) shows that the pH value of the lake section is 7.6 to 8.4 in January due to the change of WT. pH value is very stable above 50 m water depth, varying around 8.2. Compared with January, the overall pH value of the water body appeared to increase in April, with a relatively high and evenly distributed pH value at 0~25 m. The pH value suddenly decreased in the 25 m water column. As the water depth increased, the pH was still 8.0 at the bottom of the water body. An increase in temperature and photosynthesis of aquatic plants in July led to the consumption of a large amount of CO_2 in the water body, which increased the pH value and alkalinity of the water body. At this time, due to various factors being most active, a diverse change in pH value was observed, especially at a water depth of 15 to 55 m, where the pH value could reach up to 9.6. Until October, the vertical distribution of pH values in the 0 to 20 m water body was relatively stable, ranged between 8.4 to 8.8, and it gradually decreased after the 20 m depth.

From a spatial point of view, the vertical pH change in the northern part of Lake Lugu in January was slightly more pronounced than in the southern part, but the difference was not significant. The vertical variation of pH in southern waters was stable. In April, pH variation was observed at the 25 m and 23 m in the northern (F and G) and southern (I) water area. In July, the pH of the north–south water area of Lake Lugu showed a distinct stratification in the vertical direction, and with the pH peak appearing in the northern area. In October, the pH values in the northern and southern water bodies were consistent and stratified but suddenly changed at the 19 m water layer. The pH value of surface waters in the northern area was slightly higher than in the south.

3.2.4. Chlorophyll-a (Chl-*a*)

Chl-*a* is an important indicator of phytoplankton biomass, and the content of Chl-*a* in waters reflects the number of algae in the water to some extent and is closely related to algae growth activity of algae, water transparency, nutrient salt concentration, and self-suspending characteristics [38]. Compared with EC, DO, and pH, the vertical stratification of Chl-*a* in Lake Lugu was not obvious, but the seasonal variation was significant. Seasonal analysis indicated that Chl-*a* content showed obvious seasonal variation. It peaked in summer and was lowest in winter. In January, the vertical distribution of Chl-*a* content was relatively uniform, and the concentration gradient at the 45 m water layer was greatest and remained almost unchanged in water layers below 55 m. Throughout April, the vertical change in Chl-*a* content was unclear and showed no obvious stratification. In July, minimum and maximum Chl-*a* content was recorded at surface water and 20 m water depth, respectively. In October, the average Chl-*a* content was higher than in January and April, and changed sharply in the 20 m water column. Overall, the Chl-*a* concentration gradient was larger in the thermocline, and comparison analysis showed that Chl-*a* fluctuated more vertically in October and the distribution was more evenly distributed in January and April.

According to the experimental results in January, April, and October 2015 (Figure 6), it could be seen that the Chl-*a* content differed to some extent in the spatial distribution, and there was a vertical change in Chl-*a* in the water layer. The change was more obvious in the northern part than the southern part of Lake Lugu, with the Chl-*a* content in the surface water being greater in the north than in the south.

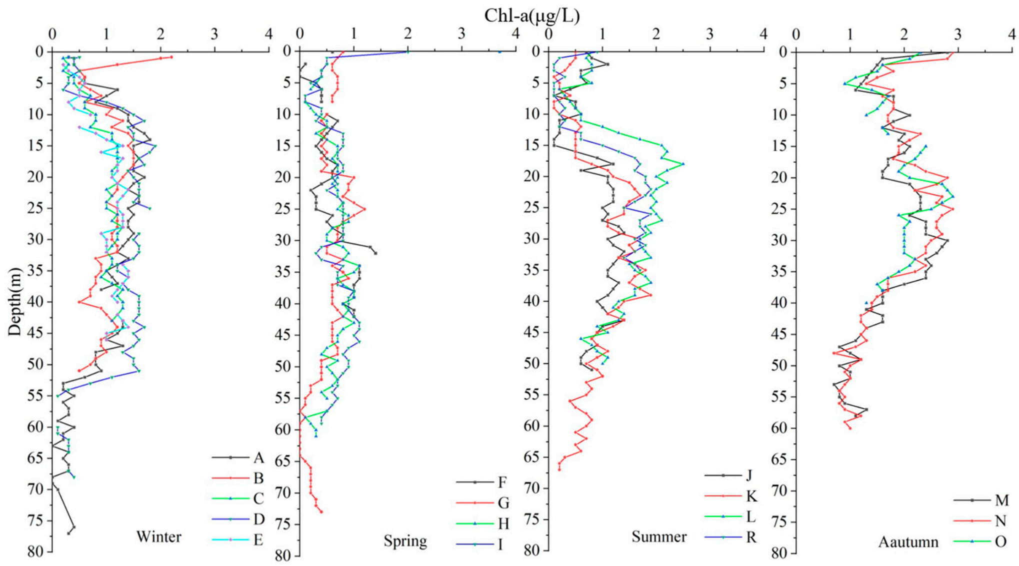

Figure 6. Seasonal variations in vertical chlorophyll- *a* (Chl-*a*) in Lake Lugu.

3.3. Relationship between Changes in Lake Lugu WT Stratification and Water Body Parameters

3.3.1. Water Mixing Type of Lake Lugu

The lake WT and temperature demonstrated obvious seasonal variation. Accordingly, the thermal stratification phenomenon of the lake water body also showed different seasonal patterns [38]. Therefore, most classifications of lakes are proposed based on thermal stratification and mixed types [39]. The vertical cross-section of WT in Lake Lugu revealed that the vertical distribution of WT in winter was close to the same temperature state, a positive temperature layer distribution in spring, summer, and autumn, and an obvious thermocline appeared in summer and autumn. Therefore, according to the lake classification scheme proposed by Lewis [40] based on revising previous work and the special geographical location and current situation of Lake Lugu, the lake-water mixing mode conformed to the characteristics of winter mixing, spring stratification formation, and stable stratification in summer and autumn, which indicate a warm single mixed lake.

3.3.2. Relationship between Seasonal Variation of Temperature Stratification and Spatial-Temporal Distribution of DO

The exponential method was used to determine the WT stratification type [41], if α = the total storage of volume flow divided by total storage capacity, when $\alpha < 10$, it represents a stable stratified type, and when $\alpha > 20$, it represents a completely mixed type. Lake Lugu has a low capacity of 1.953 billion m^3, and the annual volume of water entering the lake is 1.1 million m^3. Calculation results showed it had an $\alpha < 10$. It could be seen that the vertical WT distribution of the Lugu was stable, and the type of stratification matched the measurement results. Due to the thermal stratification of the water body, the exchange of material and energy between water layers was limited, causing an obvious response of water quality parameters. For deep-water lakes, a weaker hydrodynamics and longer retention time of water column refer to an uneven heat transfer from the water column, causing differences in the density of hot and cold-water columns, leading to differences in the physicochemical properties of different water layers and significant changes in the DO of the water column within the thermocline.

There are many factors that influence the vertical distribution of DO in a lake, such as depth, atmospheric temperature, basin shape, hydrothermal stratification, and biological effects. Lake Lugu is a deep-water arc, with its seasonal DO stratification greatly affecting WT stratification and vertical WT stratification greatly influencing the vertical DO distribution. Its upper water body was in direct contact with the atmosphere and was greatly disturbed by winds. Photosynthesis of aquatic plants in the temperature layer was strong, and the vertical mixing of DO was relatively uniform. However, the vertical mixing of DO was severely suppressed. Inside the isothermal bed, there was a very small number of aquatic plants, weak light, low rate of photosynthesis, and the decomposition of organic matter further increased the oxygen consumption of the water body. The presence of thermocline seriously blocked the exchange of substances and energy in the upper and lower bodies due to the isothermal water body. A long-term stagnation of water bodies at the mean temperature layer prevented the timely replenishment of DO in the upper layer of water bodies, causing the rate of oxygen consumption in the lower layer to exceed the rate of oxygen replenishment, resulting in the continuous decrease of DO content in the mean temperature layer of Lake Lugu and gradual development of anaerobic conditions.

The effect of temperature stratification of Lake Lugu on the vertical distribution of DO was comparable with that of Lake Wanfeng [42] and Korean Reservoir [43], and the seasonal stratification of WT resulted in seasonal stratification of the vertical distribution of DO. In winter, solar radiation was weak and the temperature was low, causing the lake water to release latent heat to the outside. The oxygen-rich water in the thermocline supplemented the consumption of DO in time, allowing DO to be evenly distributed in the vertical direction. The water level in the northern part of Lake Lugu was deeper, and the surface WT was higher. The thermocline was located at the 50 m water layer, where the temperature gradient changed greatly. At the same time, DO decreased sharply at 50 m, and the vertical change in WT in the south was uniform. The water layer below 55 m had a DO concentration <4.0 mg/L, indicating a state of hypoxia.

The thermal stratification initially formed in spring, and the existence of the thermocline effectively prevented the vertical convective mixing of water. The vertical distribution of DO in the thermocline was relatively uniform, and the DO in the thermocline gradually decreased and changed slowly. The depth of thermal rock formation in the northern water was lower than in the south and moved 5 m, shifting the vertical position of the DO in the northern water downwards compared with the southern water. The thermal stratification was stable in summer, DO vertical distribution in the temperature change layer was uniform, and the DO of the temperature change layer as a whole was lower than in April. The possible reason for such observations could be due to (1) decreased DO as temperature increased, (2) weakening of the hydrodynamic force of the temperature change layer, (3) day and night migration of aquatic organisms. In WT, DO changes were more complex and diverse. A peak was observed at the 20 m depth, and the DO decreased sharply above and below the 20 m depth. Factors causing extreme DO changes are very complex and can be broadly divided into physical factors, biological factors, and the combined effects of the two. In the case of Lake Lugu, physical factors were almost eliminated because of the physical influences and DO extremes due to WT or high-density water replenishment. The temperature difference between the Lake Lugu water body monitoring zones was small and mainly depended on precipitation. The position of the extreme value of DO cause by biological factors was consistent with the transparency of the water body [44]. Lake Lugu belongs to the Class I water quality with a transparency of 12 to 14 m. At the same time, Lake Lugu contained aquatic organisms that performed photosynthesis, because of its high altitude and the strong ultraviolet radiation in summer. To avoid the sun's ultraviolet radiation, the aquatic organisms mostly proliferated at about the 20 m water layer, which was in the thermocline. The presence of the thermocline severely inhibited the upward transport of O_2 produced by photosynthesis, resulting in low DO in the variable and mean temperature layers. In autumn, the DO decreased sharply at around 20 m depth. In the 0~20 m water layer, the aquatic organisms produced large amounts of DO by photosynthesis, and the strong turbulent mixing effects caused the DO to diffuse rapidly and made the vertical mixing more uniform in the 0~20 m water layer, leading to a very small DO concentration in the mean temperature layer and an anaerobic environment.

3.3.3. Influence of WT Stratification on the Temporal and Spatial Distribution of pH

The water pH was mainly controlled by the CO_2 content and HCO_3^- concentration, while the water CO_2 content was affected by WT, dissolved ions, microorganisms, and other factors [45]. Lake Lugu is a natural freshwater lake with a transparent water body. Therefore, a pH change in the water body was mainly related to the photosynthesis of aquatic organisms. The surface water body had sufficient light, a large plankton population, strong photosynthesis, and a large consumption of CO_2, which disrupted the equilibrium process of $CO_2-H_2CO_3-HCO_3^- -CO_3^{2-}$, causing the water to have an increased pH and weak alkalinity. Photosynthesis was very weak in the deep-water layer because light could not penetrate. In addition, mineralization and degradation of organic matter at the water–sediment interface generated a large amount of CO_2 and small molecular organic acids. Due to the cumulative effects of CO_2 and small molecular organic acids at layers closer to the bottom, their corresponding pH value was small. The existence of thermocline seriously blocked the exchange of materials and energy between the upper and lower water bodies. Comparatively, the lower water body had a long retention time and a slow molecular diffusion rate, resulting in a slower change in pH.

Similar to DO, the temporal and spatial pH distribution in Lake Lugu also demonstrated seasonal stratification characteristics. In winter, the water body released latent heat and was mixed vertically at the temperature change layer > 50 m, causing the vertical pH distribution to be uniform and more hydrodynamic conditions with deeper water depth. Thus, a weaker pH was observed in the northern water at a deeper water level, with a sudden change and considerable decrease observed at a water depth of 51 m. In spring, the pH value was slightly higher than in winter, which was related to the consumption of CO_2 in water due to the photosynthesis of aquatic organisms and the gradual decrease in the pH value of thermocline. Thermocline and weak stability in spring resulted in very weak pH change in the isothermal layer. In July, the pH value showed a low distribution trend at both ends, while it was high in the middle. Based on the vertical distribution characteristics of DO, it could be inferred that the pH value was higher at about 20 m. However, unlike this inference, the pH values of the northern and southern water bodies peaked at about 30 m and 24 m, respectively, and the pH value of the northern water body changed significantly, which may have been caused by the physical effects of warming and cooling of the water body, or the downward shift of the pH pole position due to gravity flow or density flow. In the north, the water level was deeper and the surface WT ranged between 20.5 °C to 21 °C, which was beneficial to the growth of aquatic organisms, leading to a greater amount of photosynthesis and CO_2 consumption, and a significant increase in pH. In October, the vertical distribution of pH in the 0 to 20 m water column was constant, and the higher pH was due to the cumulative effect of continuous CO_2 consumption by the photosynthesis of aquatic plants.

3.3.4. Effect of WT Stratification on the Spatiotemporal Distribution of EC

The EC of water was proportional to the concentration (or activity) of ions dissolved in the water, which mainly reflected the total amount of soluble ions in the water. The molecular formula of water (H_2O) shows that water is composed of electrically neutral molecules rather than ions, natural water is a good conductor of electricity, and it obeys Ohm's law. In lake water, a large number of substances dissolve, dissociate, and form electroactive ions, which can increase the conductivity of the water column, mainly controlled by soluble substances and temperature [46]. Figures 2 and 3 show that in the vertical direction, the seasonal stratification trend of EC and WT was consistent, suggesting that temperature was the main factor affecting EC. Based on its characteristics, the water quality of Lake Lugu is classified as Class I and has high transparency. The salinity of the lake water is determined by the total ion concentration in the water body. In the vertical section of the water body in lake Lugu, the salinity was almost constant (~0.10‰), ignoring the effects of ion concentration on conductivity and the relationship between EC and WT in each vertical section (Table 2).

Table 2. The relationship between electrical (EC) conductivity and water temperature (WT).

Sampling Point	Winter		Sampling Point	Spring	
	Equation	*p*		Equation	*p*
A	$C = -0.015T + 0.289$	−0.981 **	F	$C = 0.004T + 0.121$	0.999 **
B	$C = -0.004T + 0.184$	−0.464 **	G	$C = 0.004T + 0.122$	0.997 **
C	$C = -0.004T + 0.187$	−0.312 *	H	$C = 0.004T + 0.121$	0.996 **
D	$C = 0.004T + 0.103$	0.346 *	I	$C = 0.004T + 0.187$	0.999 **
E	$C = 0.004T + 0.096$	0.912 **			
Sampling Point	**Summer**		**Sampling Point**	**Autumn**	
	Equation	***p***		**Equation**	***p***
J	$C = 0.004T + 0.122$	0.997 **	M	$C = 0.003T + 0.143$	0.989 **
K	$C = 0.004T + 0.121$	0.999 **	N	$C = 0.003T + 0.144$	0.988 **
L	$C = 0.004T + 0.122$	0.999 **	O	$C = 0.003T + 0.146$	0.984 **
R	$C = 0.004T + 0.121$	0.999 **			

Notes: ** extremely significant correlation, $p < 0.01$; * Significant correlation, $p < 0.05$, *C*: EC (mS/cm), *T*: WT (°C).

Correlation analysis in Table 2 shows a significant and positive correlation between electrical EC and WT in winter (except in the water body at the northern part of Lake Lugu), spring, summer, and autumn, and that EC and temperature had a simple linear function. The thermal stratification of the water column was formed in April, and the stratification was stabilized in July. Due to the blocking effect of the thermocline, the EC fluctuated greatly. At the same time, when the solar radiation increased, the temperature increased, WT increased, and the molecular and ion movement rate accelerated, resulting in the exchange rate between the northern and southern part of Lake Lugu, causing the conductivity and the WT to be extremely similar, which could be summarized as the following function of conductivity and WT in April and July: $C = 0.004T + 0.12$. In October, a decrease in temperature, WT and difference in water density led to a downward shift of the thermocline position and a decrease in the slope between EC and WT, but no significant difference between the north and south water bodies. The functional relationship between EC and the WT on the vertical section of the water body was close to: $C = 0.003T + 0.14$. In winter, the vertical turbulence effect on the water body was enhanced and the electrical EC changed uniformly in the vertical direction. However, the EC of the water body in the northern part of Lake Lugu was inversely correlated with WT, showing a relationship: $C= -0.008T + 0.22$; while that in the south was positively correlated, showing a relationship: $C= 0.004T + 0.10$. In principle, EC was positively correlated with temperature and ion concentration, but this inverse correlation observed in the water of the northern part of Lake Lugu may have been due to an increase in the concentration of H^+ and soluble substances concentration in the northern water. The body temperature was lowered, the concentration of ions positively affected EC, and the effects of speed exceeded that of WT. The functional relationship between EC and WT in the vertical section of the Lake Lugu water body was concordant with the results of a previous study, $C(T) = aT + b$ [47].

The presence of thermocline effectively inhibited convection, turbulence, and molecular exchange in the upper and lower waters of the lake, seriously impeding the exchange of material and energy, thus affecting the vertical distribution of EC in the presence of thermal stratification. Therefore, thermal stratification in water also had a certain impact on the vertical distribution of EC. Taking the phenomenon of no stratification in winter as the reference to represent the relationship between the EC and temperature of the whole lake, it demonstrated a relatively high correlation between the EC–temperature, with some differences between the different layers (Table 3). The correlation analysis in Table 3 showed a significantly positive correlation between the EC and WT of the thermocline, epilimnion, and hypolimnion. The slope between EC–temperature increased gradually in the vertical direction of the monitored section, indicating that the influence of temperature on EC increased with increasing water depth.

Table 3. The functional relationship of epilimnion, thermocline, and hypolimnion between electrical conductivity (EC) and water temperature (WT).

Lake Stratification	Equation	*p*
Epilimnion	$C = 0.0065T + 0.079$	0.964 **
Thermocline	$C = 0.0082T + 0.063$	0.900 **
Hypolimnion	$C = 0.0334T - 0.176$	0.628 *

Notes: ** extremely significant correlation, $p < 0.01$; * Significant correlation, $p < 0.05$, C: EC (mS/cm), *T*: WT (°C).

3.3.5. Effect of WT Stratification on the Spatiotemporal Distribution of Chl-*a*

Chl-*a* is the pigment that makes plants green and is an important component of phytoplankton in water. Photosynthesis in water was mainly performed by phytoplankton [48]. Considering that phytoplankton contain Chl-*a*, it is commonly used to estimate the number of existing phytoplankton and photosynthesis and as a water quality monitoring indicator [49,50]. According to the China National Environmental Monitoring Center's evaluation method and technical classification regulations of lake (reservoir) eutrophication [51,52], the Chl-*a* of Lake Lugu was less than 3.09 μg/L in the four seasons of the year, suggesting that it is an oligotrophic lake. The water quality of Lake Lugu was classified as Class I in 2020, indicating good water quality. Further, its total nitrogen content based on the single evaluation index of lakes and reservoirs showed that Lake Lugu was classified as a Class I lake and had a nutritional status index of 13.2, further confirming it as an oligotrophic lake.

The Chl-*a* concentration in Lake Lugu varied significantly with the seasons, with a small growth peak in summer and autumn. The peak of Chl-*a* appeared at the surface water and after water stratification because WT and light conditions were suitable for algae growth. In the mean temperature layer, the Chl-*a* level was more uniform. In winter, Chl-*a* was higher when the surface WT of Lake Lugu dropped to its lowest level for the whole year, and during this period, Lake Lugu was controlled by rotating winds. The decrease in WT in the thermostat layer caused a thickening effect in the upper water body, increasing the instability of the water body in the thermostat layer. In addition, the continuous non-directional wind made the lower water body rich in nutrients and surpassed that of the upper water body. Overall, the vertical distribution of Chl-*a* in Lake Lugu fluctuated slightly. In summer, the southwest monsoon predominated. At this time, precipitation reached its highest levels of the year and the lowest Chl-*a* levels were recorded in the surface water. In summer, the temperature rose and due to strong solar ultraviolet radiation, algae were most active at a depth of 20 m, whereby Chl-*a* content peaked. On the whole, the variation of Chl-*a* content in the thermocline was more complex in summer, and the Chl-*a* content in the uniform temperature layer was more stable. In autumn, when the southwest monsoon retreated and algae growth was more prosperous, a higher Chl-*a* was recorded, causing a sudden jump at ~20 m. In the water layer below 40 m, Chl-*a* was evenly distributed vertically.

3.4. Limitations and Implications

First, this study analyzed the seasonal dynamics of WT and its vertical stratification structure based on monitoring data, and discussed the seasonal stratification characteristics of Lake Lugu water chemistry. However, long-term and high-frequency observations of the thermal stratification transition and its critical periods are lacking in terms of hydrodynamic profiles, nutrients, and phytoplankton. Second, due to the limited number of monitoring sites, the results may not be representative of the whole lake. With the improvement of monitoring systems and methods, this problem may be solved in the near future. Third, the impact of human activities on the water quality of Lake Lugu in the context of urbanization was not analyzed. In addition to climate change, human activities (population, GDP, impervious area, industrial structure, non-point pollution, etc.) also cause water quality changes in Lake Lugu. In the context of complex climate change and anthropogenic disturbances in the future, much work remains to be done to gain a more comprehensive and in-depth understanding of the thermal stratification characteristics of the water column in Lake Lugu and other similar lakes in the region and their ecological and environmental impacts (e.g., revealing their effects on changes in phytoplankton community structure and even the driving mechanisms of water blooms).

4. Conclusions

Lake Lugu is a typical warm single mixed lake. The stratification is characterized as mixed in winter and stratified in summer and autumn, and the lake is a single mixed lake. Lake Lugu thermal stratification controls the vertical distribution and variation of DO, pH, EC, resulting in the vertical stratification pattern of DO, pH, EC, and synergistic variation of thermocline. Meanwhile, WT stratification affects the spatial and temporal distribution of pH, EC, DO, and Chl-*a*. In winter, the water bodies are in the mixing period, and the water chemistry parameters EC, pH, and DO are evenly distributed vertically. In summer, the vertical stratification of EC, pH, and DO was more obvious, and the peak of pH and DO appear in the thermocline, and the trend was decreasing from the peak upward and downward.

The salinity of the Lake Lugu water column remains basically constant (about 0.10‰), and there is a simple linear function between EC and WT without considering the salinity effect, both in the vertical section and in the variable temperature layer, thermocline, and mean temperature layer. The results of correlation analysis showed that EC and WT were significantly and positively correlated in winter (except for Lake Lugu northern water body), spring, summer, and autumn, and the inverse correlation in Lake Lugu northern water body might be due to the increase of H^+ and soluble matter concentration in northern water body with the decrease of WT.

The spatial distribution pattern of Lake Lugu Chl-*a* content: south > north, which is due to the different effects of geographical location, lake current, and wind direction on Chl-*a* in the same lake at different depths. In addition to the above reasons, human activities are also one of the main reasons for the increase of Chl-*a* content in Lake Lugu, and the locations with the highest increase of Chl-*a* content are the most active tourist activities in Lake Lugu, which should be of great concern. With the seasonal formation and disappearance of the Lake Lugu thermocline, there will be an impact on the water quality of Lake Lugu. Therefore, to protect the ecosystem of Lake Lugu, water quality monitoring should be conducted in summer and autumn, and a rapid emergency mechanism should be developed in advance.

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