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RESEARCH PAPER

Limnological Characteristics of Inland, Glacial Lakes on the Horseshoe Island (Antarctica)

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Abstract

Antarctica is a continent with extreme climatic conditions, with many lakes and ponds with ecological status varying from ultra-oligotrophic to hypereutrophic. Horseshoe Island is situated in Marguerite Bay, in the western Antarctic Peninsula. In this research, we purpose to determine the limnological characteristics of four lakes on Horseshoe Island (Col 1, Col 2, Skua and Zano). Water samples were taken once (during the summer period) from one station in each of the lakes for chemical analysis. The Trophic State Index (TSI) was calculated based on Secchi depth, chlorophyll-a, and total phosphorus concentrations. Phytoplankton were sampled from the same stations, except for Lake Zano, because of the ice cover. Phytoplankton community indice (Q) was calculated. Total phosphorus concentration for Lake Col 1, Col 2, Skua and Zano were measured as 0.6, 0.65, 3.0, 4.6 mg/m^3, respectively. Based on total phosphorus, these four lentic systems are oligotrophic. TSI values pointed out oligotrophy and mesotrophy in the lakes. Lake Skua was found to be excellent quality (0.59 mg/l) while Lake Col 1 (0.72 mg/l) and Lake Col 2 (0.68 mg/l) were found to be good quality according to total phytoplankton biomass. The ecological status of the lakes is prediction to be of medium quality based on cyanobacteria biomass. This may be due to the rapid increase of Cyanobacteria in the short summer period as well as nutrient enrichment. Based on the Q indice, Lake Skua (4.2) is of excellent quality, Lake Col 2 (4) is of good quality, and Lake Col 1 (2.73) is of moderate quality in ice-free period. Because these lakes are under stressors such as climatic pressure (duration of ice cover) and natural eutrophication processes, regular monitoring of the lakes on the Antarctic continent is recommended

Introduction

Polar and glacial lakes are particularly sensitive to environmental change. Antarctic lakes are reported to show extremely rapid physical properties freshwater ecosystem changes and combined ecological responses (Quayle et al., 2002; Convey & Peck, 2019; Özkan, 2023). Antarctica, with its dry valleys, is considered the coldest and most arid desert system in the world. The Antarctic Continent, with its extremely low temperatures, frequent freeze-thaw cycles, and limited availability of water sources, has serious environmental stress mechanisms in terms of life (Cowan et al., 2014). The continent is considered the most valuable continent in the world in terms of the climate and protection of ocean ecosystems. Antarctica, with its large ice sheets, acts as a buffer against the effects of global warming (Cavicchioli, 2015). It has been exposed to fewer environmental factors than other parts of the world, and remains relatively intact and protected. In contrast, the World Meteorological Organization Report (Anonymous, 2023) reported that the annual

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temperature value between 2023-2027 will exceed the temperature between 1850-1900 by approximately 1.1-1.8°C, and that this temperature increase will affect the northern polar temperature change the most, especially in the winter season, and will increase by more than three times.

Limnological examination of glacial lakes is important in terms of not only providing information about the lakes for which there is little information in the literature but also revealing the effects of climate change, which is a serious problem today. Lentic systems are stagnant water systems that are affected by the rock structure and climate of the basin in which they are located. Each lake has its own internal dynamics (Wetzel, 2001). There has been a change in the food web structure of lakes due to climate change. It has been stated that the increase in food availability and high temperatures may increase phytoplankton production, the decrease in lake water level due to the decrease in precipitation will cause changes in the nutrient status and acidity of lakes with low buffering capacity, and therefore eutrophication problems may become more serious (Verdonschot et al., 2010).

Horseshoe Island is located in Marguerite Bay in the west of Antarctica. When the island is examined based on its geological structure, it can be seen that it has a complex structure. In regions devoid of ice, plutonic rocks and gneisses consisting of granite and gabbro were found. Searie, with an altitude of 537 m, and Mount Breaker, with an altitude of 879 m, are volcanic mountains located in the north of the island. The most important natural area of the island is the Shoesmith Glacier, which covers an area of approximately 6.5 km^2. The glacier extends along the east-west direction of the island (Yıldırım, 2019). Many lakes in extreme Antarctic conditions are unproductive systems and ice covered perennially or most of the year (Wharton et al., 1989; Laybourn-Parry & Wadham, 2014). Although most lakes are reported to be ultra-oligotrophic or oligotrophic, there are lakes with higher trophic conditions because of natural eutrophication due to the enrichment of nutrients. Several data from phytoplankton communities and diversity have been reviewed for lakes with contrasting trophic states in Continental and Maritime Antarctica (Izaguerre et al., 1998; 2021).

Most lakes on Earth are of glacial origin. This constitutes 74% of the total freshwater lakes and 3/4 of the lentic systems in terms of the total lake area (Kalff, 2003). In recent years, both biological and physicochemical parameters of glacial lakes have been investigated to reveal the effects of climate change and to contribute to ecological evaluations regarding decreasing freshwater resources (Sommer, 1986; Padisak et al., 2009; Sharma & Kumar, 2017; Roșca et al., 2020).

Limnological studies on the phytoplankton ecology of the Antarctic continent and the diversity of Antarctic inland waters began in the early 1960s (Goldman et al., 1963). The first physiological studies on microalgal diversity were carried out at the end of the nineteenth century (Izaguirre & Mataloni, 2000). The most comprehensive study of phytoplankton species composition in glacial regions was conducted by Kang et al. (2001) in the Weddell Sea. They identified 86 species in their research. The genera identified were diatoms (*Actinocyclus, Azpeitia, Banquisia, Chaetoceros, Corethron, Coscinodiscus, Cylindrotheca, Eucampica, Fragilariopsis, Haslea, Manguinea, Navicula, Nitzschia, Odontella, Porosira, Proboscia, Pseudo-nitzschia, Rhizosolenia, Stellarima, Thalassiosira, Trichotoxon),* Flagellates (*Bodo, Choanoflagellates*), Ciliates (*Cryptomonas, Dictyocha, Gymnodinium, Mantoniella, Parvicorbucula, Phaeocystis, Prymnesium, Pyramimonas*). Since then, algal groups, such as Chlorophytes, Chrysophytes, Cryptophytes, Diatoms, Dinoflagellates and Cyanobacteria, have been reported in Antarctica (Lizotte, 2008).

Some phytoplankton and algal studies have been reported from several Turkish Antarctic Expeditions during summer. According to Bizsel et al. (2019), in three different studies conducted around the Shetland Islands in Antarctica in 2007, in Svalbard-Kongsfjord in the Arctic in 2015, and in the Chilean Research Base Yelcho in Antarctica in 2018, phytoplankton species were identified, the diatom communities were dense, and the most dominant genus was reported to be *Cyclotella*. Feyzioğlu et al. (2019) conducted zooplankton, phytoplankton, and bacterioplankton sampling at seven stations on the island of Svalbard, up to 80° north latitude. Kıyak and Cura (2019) reported that phytoplankton diatom groups were dominant in the lakes of King George Island, Antarctica, and identified a dinoflagellate species, *Dissodinium* sp. Benthic algae in some lakes in Antarctica was investigated by Solak et al. (2019).

In this study, we aimed to provide some limnological aspects that characterize phytoplankton in lakes of Horseshoe Island in summer. All of these lakes are shallow, small, freshwater, and ice covered most of the year. It also provided an assessment of the quality status of Col 1, Col 2, Skua, and Zano lakes on Antarctic Horseshoe Island based on water quality values and phytoplankton indices.

Material and Methods

Study Area

Horseshoe Island, where the Turkish Scientific Camp is located, is located in the west of the Antarctic Peninsula (Yirmibeşoğlu et al., 2022). The island is located on the western coast of the GRAHAM territory, and is 12 km long and 6 km wide. Sampling was performed on four lakes on the island (Col1, Col2, Skua, and Zano) in February 2023 during the Seventh Turkish Antarctic Expedition (TAE VII) (Figure 1).

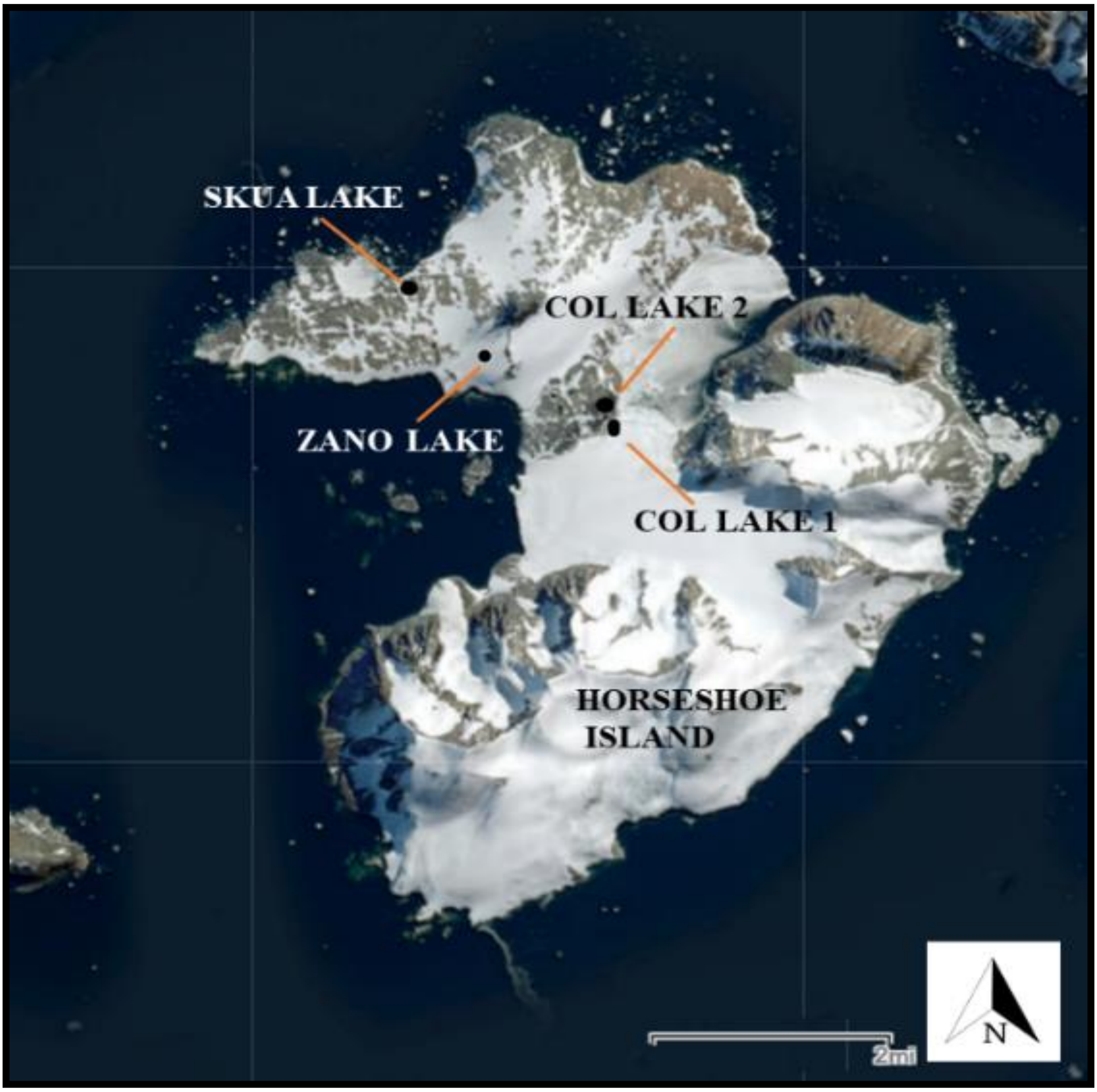

Figure 1. The location of Lake Col 1, Lake Col 2, Lake Skua and Lake Zano in Horseshoe Island

Sampling methods and preservation

Water samples for some chemical parameters and quantitative phytoplankton analysis were taken with a Ruttner (HydroBios) water sampler from one station in each of the lakes. The sampling was carried out in accordance with the TS ISO 5667-4 (2019). Because Lake Zano is covered with ice, only water samples were taken from the shore, and phytoplankton samples could not be collected. For qualitative phytoplankton sampling, vertical and horizontal shots were taken from lakes using a 10-micron mesh phytoplankton net. Dissolved oxygen (DO), pH, water temperature (WT), and electrical conductivity (EC) values were measured with the YSI brand multiparameter during field work, and turbidity was measured on-site with an EXTECH brand turbidity meter. Additionally, the Secchi depth was determined using a 20 Ø Secchi Disk (HydroBios). Readings were taken from each station 3 times. The collected water samples were frozen at –20°C in containers with polyethylene lids and transported via a cold chain. The samples collected for phytoplankton counting and identification were stored in polyethylene lidded containers with Lugol's solution (EN, 16698). The mouths of the containers were covered with parafilm and transported via cold chain. For chlorophyll-a (Chl-a) analysis, water samples (2 L from each lake) were filtered through a Whatman GF/C filter. During the filtration process, 1 ml of 1% $MgCO_3$ suspension was added, and the filter papers were wrapped in aluminium foil, frozen at -20°C and transported via a cold chain (Strickland & Parsons, 1972). Information about the locations, maximum depth, Secchi depth, pH, WT, DO, and EC of the sampling stations is given in Table 1.

Chemical Analyses

Total phosphorus (TP) analysis of the water samples was performed using TS EN ISO 15587-1.2 and TS EN ISO 17294-1.2 methods. The total nitrogen (TN) concentration was determined using the SM 4500 Norg B and SM 4110 B methods, and the total organic carbon (TOC) content was detected using the TS 8195 EN 1484 method. Orthophosphate phosphorus (PO_4-P) was determined using the ascorbic acid method according to APHA (1998). Ammonia nitrogen content was determined using the Nesslerization method. In this method, the colour intensity, depending on the concentration of the yellow colour given by the Nessler reagent, was determined by measuring it at a wavelength of 410 nm using a spectrophotometer. Nitrite-nitrogen was determined by measuring the colour formed by the diazonation of sulphanilic acid and N-1-naphthylethylenediamine dihydrochloride in a spectrophotometer at a wavelength of 523 nm. Nitrate-nitrogen was determined by measuring the yellow colour formed as a result of the reaction between nitrate ions and brucine sulphate in the water sample at 410 nm using a spectrophotometer. Total hardness and alkalinity analyses were performed according to the procedures described by APHA (1998). All water quality analyses for each station were repeated 4 times.

Phytoplankton Analyses

The water samples were placed in Hydro-Bios plankton counting chambers and kept overnight. Phytoplankton count was determined using an inverted microscope (Zeiss Brand) (Utermöhl, 1958). Phytoplankton identification was performed by examining settled water samples or samples taken with a plankton net under a binocular microscope (Zeiss brand binocular microscope 100x, 200x, 400x) according to the taxonomic literature (Cox, 1996; Hustedt, 1930; Huber-Pestalozzi, 1938; Huber-Pestalozzi, 1942; Huber-Pestalozzi, 1950; John et al., 2002; Komarek & Fott, 1983; Komarek & Anagnostidis, 1999; Lind & Brook, 1980; Popovski & Pfiester, 1990; Prescott, 1973; Starmach, 1966). The latest taxonomic nomenclature for the identified species was verified using an algaebase (https://www.algaebase.org).

Phytoplankton biomass was calculated on a biovolume basis. The geometric shapes of the phytoplankton were measured using an inverted microscope (Zeiss, 200x, 400x). The biovolume was estimated according to the geometric measurements of the specimens and the formulas specified by Sun and Liu (2003). Total phytoplankton biovolume was calculated by multiplying the average cell volume of each species by the number of species according to APHA (1998).

Phytoplankton community indice (Q) were calculated according to the method of Padisak et al. (2006). In this formula: where pi = ni/N; ni biomass of the *i*-th functional group; N: total biomass of functional groups in total biomass and a factor number (F) established for the *i*-th functional group;

$$Q = \sum_{i=1}^{n} piF$$

Q indice range between 0 and 5, of which, according to the Water Framework Directive (WFD), the five-grade evaluation system can be evaluated at 0–1, bad; 1–2, tolerable; 2–3, moderate; 3–4, good; and 4–5, excellent.

In the evaluation of the ecological status of lakes, the total biomass and Cyanobacteria biomass were used with the limit values for shallow lakes specified by Sondergaard et al. (2005). Based on the total biovolume for shallow lakes: <0.68 mm^3/l pointed out excellent quality, 0.68-1.39 mm^3/l good, 1.4-3.3 mm^3/l moderate, 3.3-15.3 mm^3/l tolerable, and bad >15.3 mm^3/l; for Cyanobacteria biovolume, 0 is excellent, 0.0-0.009 mm^3/l good, 0.01-0.68 mm^3/l moderate, 0.69-3.4 mm^3/l tolerable and bad >3.4 mm^3/l. Biomass was calculated assuming that 1 mm^3/m^3 of cell volume was equivalent to 1 mg wet weight/m^3 algal biomass (Rott, 1981).

Chl-a was extracted with 90% acetone and spectrophotometrically determined (Strickland & Parsons, 1972).

The Trophic State Index (TSI) was calculated based on Secchi depth (SD), chlorophyll-a (CHL-a), and total phosphorus (TP) concentrations according to Carlson (1977).

a. $TSI_{(SD)} = 60 – 14.41 \times \ln(SD)$

b. $TSI_{(CHL\text{-}a)} = 9.81 \times \ln(CHL\text{-}a) + 30{,}6$

Table 1. Locations, depth and physico-chemical parameters belongs to lakes

	Col 1	Col 2	Skua	Zano
Coordinate	67°49´58´´S 67°13´59´´W	67°49´43´´S 67°13´36´´ W	67°48´45´´S 67°18´19´´W	67°81´97´´S 67° 26´67´´W
Maximum depth (m)	1.5	3	3	-
Secchi depth (m)	0.7	1	1	-
Water Temperature (°C)	0.8±0.1	1±0.05	3.3±0.1	0.1±0.06
Dissolved Oxygen (mg/l)	10.85±0.01	10.64±0.1	10.35±0.01	10.97±0.01
pH	10.02±0.01	10.16±0.01	8.92±0.13	8.7±0.13
Conductivity (µS/cm)	72±0.001	57±0.001	84±0.001	81±0.001
Turbidity (ntu)	0.26±0.012	2.93±0.01	0.29±0.01	0.06±0.01

c. $TSI_{(TP)} = 14.42 \times \ln(TP) + 4.15$

d. $TSI_{(Means)} = [TSI(SD)+TSI(CHL\text{-}a)+TSI(TP)]/3$

Statistical Analysis

IBM SPSS 20, MINITAP, and Canonical Correspondence Analysis (CCA) software were used to evaluate the statistical significance of the findings from all the analyses. The significance of the data was determined by one-way analysis of variance (ANOVA), and when it was significant, their averages were compared with the DUNCAN test using the IBM SPSS 20 software program. Correlation analyses were performed using the Pearson Correlations method, their averages were compared with the DUNCAN test using in the IBM SPSS 20 software program. Canonical correspondence analysis (CCA), a direct gradient analysis technique, was used to elucidate the relationship between environmental factors and height biomass of phytoplankton species in the lakes using PAST 4.03 software. The environmental variables were transformed to reduce skewness. Phytoplankton composition and biomass data were used for the analysis.

Results

Lake Col 1, Lake Col 2, and Lake Skua started to ice over the coastal area when sampling was carried out, but Lake Zano was covered with ice at all times, except for the coastal area during the study period. Because it was covered with ice and the ice could only be broken in the coastal area, the Secchi depth and maximum depth of Lake Zano could not be measured. The water temperature values were measured between 3.3 °C and 0.1°C. The dissolved oxygen of the lakes was determined to be over 10 mg/l. The pH values of Lake Skua and Lake Zano were high at the surfaces of Col 1 and Col 2 (>10) and decreased to 8.9 Skua and 8.7. The conductivity rate was very low (84-57 µS/cm) in all lakes. We estimated that this is due to the fact that lakes were not affect both sea water and sediment accumulation, with this also the low turbidity values of all lakes varied between 0.01 ntu and 2.93 ntu support this situation (Table 1).

Because Antarctica is far from anthropogenic pollution, TP and TN concentrations are expected to be low. However, in our study, while TP concentration was low, TN concentration was high, especially in Lake Col 2 (770 mg/m^3) and Lake Zano (1000 mg/m^3). The relationships between Q index, Chl-a, total biomass and Cyanobacterial biomass values and environmental parameters of all lakes were examined using the Pearson correlations, and Q index was positively correlated with TP, TN, and water temperature ($p<0.01$, $p<0.05$). However, it was negatively correlated with TOC, NO_3-N and DO ($p<0.01$). Total Biomass was significantly correlated with TP, pH, DO, EC, and water temperature ($p<0.01$). Cyanobacteria biomass was significantly correlated with TN, TOC, NO_3-N, alkalinity, turbidity ($p<0.01$), and TH ($p<0.05$). Chl-a was significantly correlated with all parameters except both TN and TOC (Table 2). The results showed that biological activities in the lake affect the concentration of nutrients. The ice cover of lakes has also been observed to affect the concentration of nutrients. For instance, the NH_3-N and NO_2-N concentrations (7.63 mg/l and 4.53 mg/l, respectively) in Lake Zano were determined to be well above those of other lakes. This situation is thought to be due to the fact that this lake is completely covered with ice, while ice melting is observed from time to time in other lakes, causing the denitrification process to take longer (Figure 2).

The scale showing the eutrophication status of lakes based on the water quality parameters reported by Wetzel (2001) was used to estimate the trophic level of lakes based on TP, and the lakes were determined to be oligotrophic. According to the TN concentration, Lake Col 1 and Lake Zano were found to be mesotrophic, while the others were oligotrophic. Lake Col 1 and Lake

Table 2. Correlation values between Chl-a, Q index, total biomass, Cyanobacterial biomass and water quality parameters

	Pearson Correlation			
	Chl-a	**Q index**	**Total Biomass**	**Cyanobacteria Biomass**
TP	0.99**	0.59*	-0.95**	0.10
TN	-0.03	0.87**	-0.42	-0.98**
TOC	-0.02	-0.89**	0.46	0.97**
NH_3-N	0.58*	0.35	-0.56	0.05
NO_2-N	0.75**	0.04	-0.51	0.53
NO_3-N	0.22	-0.75**	0.23	0.99**
TH	0.86**	-0.05	-0.54	0.70*
Alk	-0.63*	0.39	0.22	-0.91**
pH	-0.98**	-0.52	0.92**	-0.18
DO	-0.79**	-0.88**	0.96**	0.37
EC	0.93**	0.23	-0.73**	0.46
Tur	-0.62*	0.39	0.21	-0.91**
WT	0.97**	0.66*	-0.97**	0.01

*. Correlation is significant at the 0.05 level.
**. Correlation is significant at the 0.01 level.

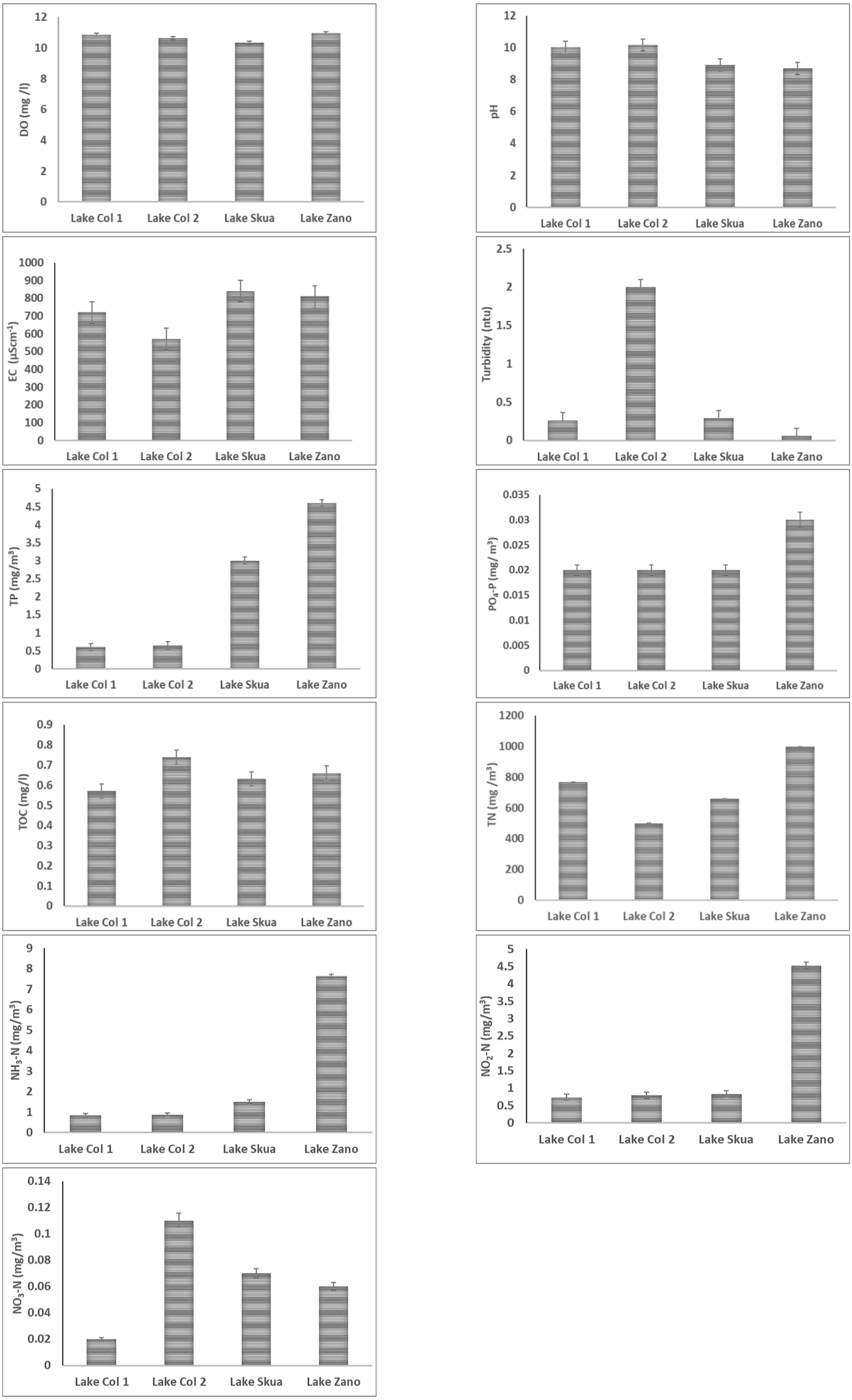

Figure 2. Environmental parameters of Lake Col 1, Lake Col 2, Lake Skua and Lake Zano

Col 2 were identified oligotrophic based on the Chl-a concentrations, on the other hand Lake Skua and Lake Zano were found to be mesotrophic (Table 3).

Evaluating the ecological status of lakes according to total biomass, cyanobacteria biomass (Sondergaard et al. 2005) and Q indice (Padisak et al. 2006), the lakes were found in "good quality." On the other hand, the increase in Cyanobacteria diversity in the lakes as well as in their biomass-based value within the total phytoplankton composition has advanced the trophic status of the lakes towards the "moderate quality." The total biomass was found to be of excellent quality in Lake Skua (0.59 mg/l). The biomass was calculated as 0.72 mg/l and 0.68 mg/l in Lake Col 1 and Col 2, respectively. These values indicate good ecological quality. According to the Cyanobacteria biomass, all lakes were identified as having moderate quality. Based on the Q indice, Lake Skua was "excellent," and Lake Col 2 were "good," and Lake Col 1 was "moderate." However, the TSI values indicated that Lake Skua was good, and the other lakes were excellent (Table 3).

In this study, 74 phytoplankton species were identified in lakes Col 1 (27), Col 2 (13), and Skua (34). Based on the CCA results, the given values of axis 1 (4.5) and axis 2 (2.0) accounted for the cumulative variance in the phytoplankton data. In the negative part of 1 axis, a weak correlation was found between *Pantocsekiella ocellata* and water temperature, total hardness, NH_3-N, PO_4-P, and alkalinity in Lake Col 1, Lake Col 2, and Lake Skua, whereas a strong correlation was found with TN. In the positive part of axis 2, a correlation was detected between alkalinity and *Merismopedia tranquilla* in all lakes (Figure 3).

All lakes were evaluated as oligotrophic depending on phytoplankton functional groups, which were generally detected as L_o codes, identified in deep and shallow-oligo to eutrophic and medium to large lakes. Lake Col 1 was dominated by H1 and TC species; Col 2 by Y species; and Skua by N, B, and MP species (Table 4). When we looked at the trophic evaluation of the lakes based on phytoplankton composition, we found that all lakes contained species that were characteristic of oligo-mesotrophic lakes.

Discussion

Limnological studies on glacial lakes and freshwater in the Antarctic continent began in the 1950s. In these studies, it was reported that the trophic state of the lakes was ultraoligotrophic and oligotrophic (Mathews, 1956; Angino et al., 1964; Goldman et al., 1972). Several researches on Antarctic lakes have been carry out with a single sample for each year or several samples during the year depending on Antarctic weather conditions, and these studies have been conducted mostly by researchers from countries with permanent bases in the region. Another factors affecting lake researches are the ice cover and ice thickness of lakes. Investigated lakes in Thala Hills, East Antarctica, were compared in 1967-68 and 1988 to discuss changes in some chemical parameters of lakes. It was reported that the phosphate content of the lake waters reached 750 µg P/l and the ammonia content reached 1300 µg N/l, which may be due to global warming, increased thawing of permafrost, exposing subsurface organic matter to meltwater runoff, and this may cause an increase in the trophic level of Antarctic lakes (Kaup, 1998). A study of nine lakes and ponds with different trophic statuses in Hope Bay (Antarctic Peninsula) between 1991 and 1996 found that the lakes were strongly affected by eutrophication caused by seabird activity in the area (Izaguirre et al., 1998). In research carried out in the same region in the early 20s, it was reported that lakes exhibit characteristics that can range from oligotrophic to mesotrophic depending on the phytoplankton and zooplankton composition (Izaguirre et al., 2003). Schiaffino et al. (2009) investigated the bacterioplankton communities of eight marine Antarctic lakes (Hope Bay, six lakes in the Antarctic Peninsula and two lakes in the Potter Peninsula, King George Island) with a wide trophic status and geographical distribution range and detected species belonging to Bacteroidetes, Actinobacteria, Betaproteobacteria, and Cyanobacteria. In the research we conducted in 2023, although the lakes were oligotrophic according to the orthophosphate and TOC values, the lakes were found to be eutrophic, depending

Table 3. Evaluation of ecological quality of lakes depend on Secchi depth, Chl-a, total phosphorus (TP), total nitrogen (TN), total biovolume and Cyanobacteria biovolume, Q indice and Mean TSI (blue: excellent-oligotrophy, green: good-mesotrophy, yellow: moderate)

Parameters	Lake Col 1	Lake Col 2	Lake Skua	Lake Zano**
TP (mg/m^3)	0.6	0.65	3	4.6
TN (mg/m^3)	770	500	660	1000
Chl-a (mg/m^3)	2.1	1.34	6.71	5.7
Secchi depth (m)*	0.7	1	1	-
Mean TSI	31.79	32.09	43.09	26.16
Total biovolume (mm^3/l)	0.72	0.68	0.59	-
Cyanobacteria biovolume (mm^3/l)	0.42	0.02	0.25	-
Q indice	2.73	4	4.2	-

* In the colourless line, no evaluation was made based on Secchi depth.

** Phytoplankton sampling could not be done in Lake Zano.

on the total nitrogen and phytoplankton communities. Ongoing research for approximately 70 years has shown that Antarctic lakes are in the process of eutrophication. This process can be considered natural, but the high total nitrogen concentration can also be interpreted as the effect of global warming on lakes due to the increase in cyanobacteria species in the phytoplankton composition. Cyanobacteria might increase faster than other phytoplankton groups in summer and during the short ice-free period of the studied lakes. It showed that the lakes were moving towards moderate quality due to the high diversity of cyanobacteria and their high contribution in the total phytoplankton in summer.

In studies carried out between 2002 and 2014 in lakes located on the Antarctic continent and in the Peninsula, the pH value varied between 6.1-8.0 without any change. Electrical conductivity values were measured as 1094-1500 µS/cm in coastal lakes and 20-169 µS/cm in lakes located far from the influence of the sea. Dissolved oxygen (DO) concentration was measured between 10-13.8 mg/l (Heywood, 1972; Cremer et al., 2004; Izagure et al., 2003; Toro et al., 2007; Tanabe et al., 2008; Nedbolova et al., 2013; Sutherland et al., 2020). Similar results were obtained in the present study. The high DO and pH values indicate that there was no change in these lakes over time and that the

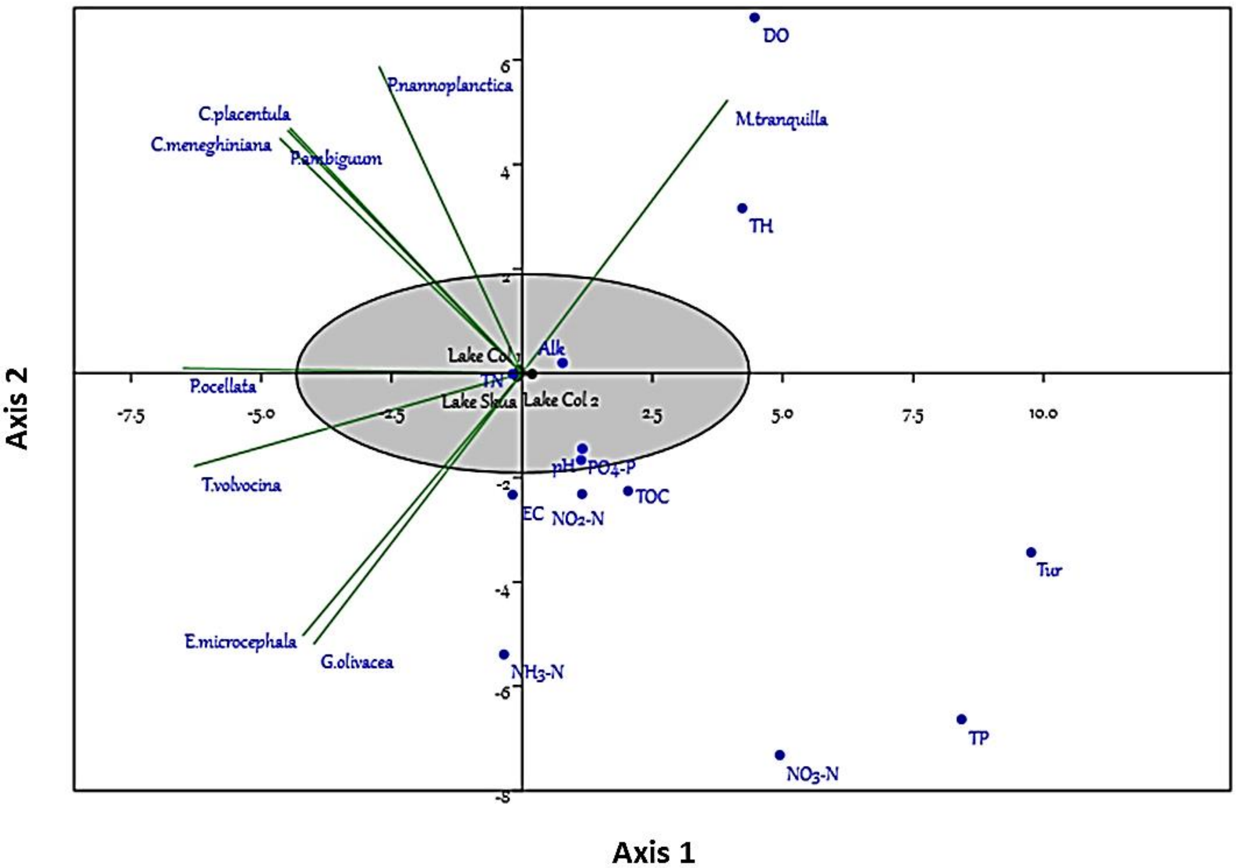

Figure 3. The canonical correspondence analysis (CCA) of lakes scores of phytoplankton relatively abundance and some water quality parameters (Alk: alkalinity, DO: dissolved oxygen, EC: electrical conductivity, NH_3-N: ammonia nitrogen, NO_2-N: nitrite-nitrogen, NO_3-N: nitrate-nitrogen, PO_4-P: orthophosphate phosphorus, TP: total phosphorus, TN: total nitrogen, TH: total hardness, Tur: turbidity, TOC: total organic carbon)

Table 4. Functional groups of Lake Col 1, Lake Col 2 and Lake Skua

Code	Habitat template	Lake Col 1	Lake Col 2	Lake Skua
B	Mesotrophic small and medium sized lakes	*Cyclotella meneghiniana*	*Cyclotella meneghiniana*	*Cyclotella meneghiniana*
N	This association can be represented in shallow lakes			*Cosmarium* sp.
N_A	Oligo-mesotrophic lakes	*Staurastrum* sp.		*Staurastrum* sp.
P	Eutrophic epilimnion	*Closterium* sp.		*Fragilaria crotonensis*
MP	Shallow, mixed lakes	*Aulacoseria* sp.	*Gomphonema* sp.	*Oscillatoria limosa*
T_C	Eutrophic lakes	*Gloeocapsa* sp.		
X1	Shallow, eutrophic-hypertrophic environments			*Monoraphidium contortum*
Y	This codon refers to a wide range of habitats		*Plagioselmis nannoplanctica*	
H_1	Eutrophic, both stratified and shallow lakes with low nitrogen content	*Anabaenopsis* sp.		
L_0	Deep and shallow, oligo to eutrophic, medium to large lakes		*Merismopedia* sp.	*Peridinium cinctum*
W1	Ponds, even temporary, rich in organic matter from husbandry or sewages	*Phacus* sp.	*Synura* sp.	
W2	Meso-eutrophic ponds, even temporary, shallow lakes	*Trachelomonas volvocina*		*Trachelomonas volvocina*

lakes were in their natural trophic processes. Similarly, TP, TOC, PO_4-P, NH_3-N, NO_3-N, and NO_2-N concentrations in glacial lakes were low, and the lakes were oligotrophic. However, TN was calculated to be high, and Cyanobacterial biomass was also found to be high in this study. TN is high in regions where anthropogenic pollution sources are located, although glacial lakes are located in regions that are not under the influence of anthropogenic pollution sources, especially the lakes on Horseshoe Island, which do not have any sources of pollution due to their location. However, recent studies in Antarctic lakes have reported high DON and TDN concentrations (590 mg DON/m^3; 18430 mg TDN/m^3) (Nedbalova et al., 2013; Sutherland et al., 2020). The TN concentrations in glacial lakes have also been reported to be 162–758 mg/m^3 (Van Colen et al., 2017). In the research, TN concentrations were found for Lake Col 1, Lake Col 2, Skua and Zano 770±0.0 mg/m^3, 500±0.05 mg/m^3, 660±0.0 mg/m^3, 1000 mg/m^3, respectively. Nitrogen and nitrogen fraction concentrations were found at low levels, but TN concentrations were high owing to the continuation of bacterial activity in Antarctic lakes (Patriarche et al., 2021). For instance, Christner et al. (2006) reported that microbial activities continue in Lake Vostoc, which has been covered with ice for approximately 15 million years, thus supporting this theory.

Phosphorus is the main nutrient that affects algal growth, but is the least abundant in freshwater, and ionized inorganic PO_4 constitutes the most important form of plant nutrition. In addition, most of the algal phosphorus released during cell lysis and decomposition is organic and undergoes bacterial degradation (Wetzel, 2001). Phosphorus is limited by growth and composition of phytoplankton communities (Reynolds, 1984), for example, *Asterionella formosa* develops when the total phosphorus concentration is 0.6-1.2 mg/m^3, while *Cyclotella meneghiniana* reaches its highest growth when the total phosphorus concentration is 8 mg/m^3. Although *Cyclotella meneghiniana* (Cod: B) was identified in all lakes in this study, the total phosphorus concentration was calculated to be very low.

Total organic carbon concentration of Lake Col1, Lake Col2, Lake Skua and Lake Zano was calculated 0.57±0.0 mg/l, 0.74±0.0 mg/l, 0.63±0.0 mg/l, 0.66±0.0 mg/l, respectively. When first observed of these increases were widely interpreted as evidence of the effects of climate change on terrestrial carbon deposited due to rising temperatures and increased frequency and severity of summer droughts (Nickus et al., 2010), but Klanten et al. (2021) reported that the DOC value was low (<0.6 mg/l) due to rare vegetation in Antarctica. In addition, it has been reported that benthic algae and bacterial activities are the sources of total carbon concentration (Christner et al., 2006; Sutherland et al., 2020; Izaguirre et al., 2021, Misic et al., 2024). In this study, it was revealed that there was a relationship between Cyanobacteria biomass and TOC in the lakes.

In this study, the ratios of total nitrogen, total phosphorus, and total organic carbon values obtained from lakes and TN:TP ratios of Lake Col 1, Lake Col 2, Lake Suka, and Lake Zano were calculated to be 0.77, 1.28, 0.22, and 0.22, respectively. In eutrophic lakes, nitrogen limits phytoplankton production, especially when the TN:TP ratio is lower than 5.6 (Reynolds, 1984). In our research, TN:TP values were determined to be well below this value, and phytoplankton production in the lakes was thought to be limited because all lakes were oligotrophic. The C:N ratios for Col 1, Col 2, Skua, and Zano lakes were 0.74, 1.48, 0.95, and 0.66, respectively. In lakes where dissolved organic matter is concentrated, as a result of the increase in the C:N ratio, there is an increase in the organic carbon concentration and a decrease in the organic nitrogen concentration. Wetzel (2001) reported that the pure protein ratio depends on the C:N ratio, and that the C:N ratio is 12 in lakes where phytoplankton develop densely. Because the duration of the lakes being covered with ice is a factor in the development of phytoplankton in glacial lakes, it is possible for the C:N ratio to be low.

The lakes studied have low biodiversity due to their location being away from anthropogenic pollution, poor in nutrients, and covered with ice during most of the year; however, some species have been identified to belong to eutrophic lake characteristics. The Lake Skua functional groups (N, B, and MP) were identified as indicator species belonging to small lakes with a similar mixture. The functional groups of Lake Col 1 and Lake Col 2 (Tc, H1, and Y) were found to be indicators of nutrient-rich small lakes and eutrophic lakes. It is well known that phytoplankton can. In Antarctica, phytoplankton is also subject to be structured by a combination of top-down, bottom-up, or competition controls of regulating factors. This is controlled by metazoan plankton, which can reach the phytoplankton from above in short periods of time for lakes in the Maritime Antarctic and Sub-Antarctic, and by limited nutrients for lakes in the Continental Antarctic (Izagure et al., 2021). Glacial lakes, especially those on the Antarctic continent, are freshwater systems that are far from anthropogenic sources and show ecological changes due to natural processes. Extreme weather conditions, and therefore the duration of the lake surface being covered with ice, is long in Antarctic lakes (Henshaw & Laybourn-Parry, 2002; Cremer et al., 2004). The water temperature of the lakes varied between 2 and and 4°C in 1964 in Antarctica (Angino et al. 1964), and the highest and lowest water temperatures of lakes have been measured at 18.2ºC and –0.8ºC in the Peninsula Region (Nedbalova et al. 2013). In this study, the water temperatures of the lakes varied between 0.1 and 3.3°C.

Evaluation of the samples based on TSI, total biomass, and Q indice was found to be between excellent and moderate quality, whereas TP and TOC concentrations were low and even low for Lake Col 1 and Skua, which were found to be of moderate quality according to Cyanobacteria biomass. Lake Col 1 was determined to be of moderate quality based on Q indice. In these evaluations, it should be taken into account that sampling was performed once during the summer period.

Conclusion

Lakes Col 1, Col 2, Skua, and Zano are located uninhabited on Horseshoe Island (Antarctica), which is covered with ice for most of the year. Among these lakes, only the British Base, which operated between 1955-69, is located around Lake Skua, and this area operates as a tourist attraction. We can list the factors affecting the natural development processes of lakes as the rock structure that forms the terrestrial environment around them, the atmosphere, changes due to icing/melting time due to climate change, and natural eutrophication resulting from dense bird populations.

As a result, the evaporation and ice cover changes of lakes vary due to climate change. In this case, it affects water quality and biodiversity, especially in glacial lakes. However, some species were identified in the phytoplankton of the lakes, including Cyanobacteria, and the TN values indicated the eutrophication process. The main reason for this is thought to be the change in the duration of ice cover due to climate change and natural eutrophication.

Ethical Statement

Not applicable.

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Author Contribution

Özden Fakıoğlu and Nilsun Demir: conceptualization, methodology, data curation, writing-original draft preparation. Mehmet Karadayı and Muhammet Furkan Topal: visualization, investigation. Gökçe Karadayı and Medine Güllüce: editing.

Conflict of Interest

The authors declare that they have no known competing financial or non-financial, professional, or personal conflicts that could have appeared to influence the work reported in this paper.

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