

Seasonal Dynamics and Trends of Environmental Conditions in Lake Louise, Georgia

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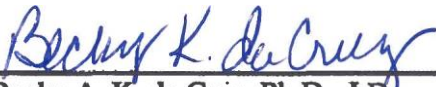


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ABSTRACT

Lakes are important aquatic ecosystems that are extensively influenced by seasonal variations. This study investigates the seasonal dynamics and trends of three environmental variables, water temperature, conductivity and dissolved oxygen (DO), in Lake Louise, a sinkhole lake located in southern Georgia. These variables were measured *in-situ* along a depth profile from January 27, 2024 to January 17, 2025. Archived data from field campaigns in 2003, 2004, and 2017 was accessed in order to test whether a recent increase in the number of hurricanes impacting the region, five since August, 2017, may have significantly altered the seasonal dynamics of the lake. Seasonal differences and trends were investigated using Dunn's test of multiple comparisons and the Modified Mann-Kendall test, respectively. The study also quantified phytoplankton in the lake using imaging flow cytometry. The results highlight the highly responsive nature of the lake's surface waters to seasonal variation and environmental impacts while conditions in the hypolimnion (deeper layers) were relatively stable and differentially anoxic over the study period; only conductivity showed an increasing trend in the hypolimnion as thermal stratification stabilized. Pairwise comparisons of seasons showed a mix of significant and non-significant differences in water temperature, conductivity, and dissolved oxygen levels within the period of study. The Modified Mann-Kendall test results for water temperature indicated a non-significant increasing trend from 2004 to 2024, although in 2003, the increase was significant. Conductivity exhibited a significant increasing trend for the period of study in 2024, and in 2017. Meanwhile, oxygen levels demonstrated significant decreasing trends in 2004 and 2024, with non-significant decreasing trends observed in 2003 and 2017. Cyanobacteria levels post-Hurricane Irma in 2017 significantly decreased in 2024, possibly due to Hurricane Helene's timing in 2024.

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LIST OF ABBREVIATION & DEFINITIONS

Anoxia: A condition when a part of a body of water, usually at depth, has negligible or no dissolved oxygen present in the water.

DO: Dissolved oxygen. Amount of oxygen gas present in water, which is essential for aquatic life to survive.

Dimictic lake: A lake that mixes twice annually, in the spring and in the fall.

Epilimnion: The surface layer of a body of water.

Hypolimnion: The cold, bottom layer of a body of water.

Metalimnion: A layer in a body of water that lies between the surface layer and bottom layer. This is also referred to as the thermocline.

Monomictic lake: A lake that undergoes a single, regular mixing period each year.

Oligotrophic lakes: Lakes containing very low concentrations of those nutrients required for plant growth.

Phytoplankton: A collection of photosynthetic microorganisms adapted to live partly or continuously in open water.

Thermal stratification: When a body of water begins to gain heat and stratify into three somewhat distinct layers.

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CHAPTER I

INTRODUCTION

Freshwater ecosystems, such as lakes, possess distinct borders and robust ecological variations making them ideal examples when examining the environmental conditions of impacting microbial communities. One of the main groups of primary producers in aquatic systems is the phytoplankton. Because of their small size and short generational times, members of the phytoplankton are extremely responsive to changes in their surroundings and closely related to the nutritional state of the waterbody (Wang et al., 2024). The ecological processes of information transfer, energy movement, and material change in aquatic environments are all facilitated by phytoplankton. The phytoplankton, as a group, is capable of adapting to a variety of ecological situations depending on the individual responses of its members. Therefore, it is essential to examine their direct or indirect reactions to ecological factors when studying the association and the condition of aquatic environments.

In aquatic environments, the location and composition of the phytoplankton are determined by a mix of chemical and physical properties that can be impacted by severe climate and weather events (Bouman et al., 2003; Latinopoulos et al., 2020; Richardson, 2008). For instance, in lakes with deep water and varying temperatures, the way water temperature is distributed vertically affects how chemical and biological factors are mixed and stratified. This has a significant impact on the entire ecosystem of the lake, including the bacterioplankton, phytoplankton, zooplankton, small animals and other organisms that inhabit it (Mullin et al., 2020; Piccolroaz et al., 2015). The distribution of nutrients after an intense rainfall can also

shape ecological dynamics in lakes. For example, during intense rainfall, eutrophic lakes, where nutrients levels are high, would have a high proportion of oxidized forms of nitrogen as compared to oligotrophic lakes with fewer nutrients. This abundance can trigger shifts in the phytoplankton association, influencing not just their biomass but also their diversity and overall abundance (Ahmed et al., 2021). Additionally, extended durations of elevated surface water temperatures in lakes can lead to severe phytoplankton blooms (Jöhnk et al., 2008), widespread fish mortality incidents (Till et al., 2019), and alterations in the community structure of phytoplankton (Baker & Geider, 2021; González-Olalla et al., 2022; Rasconi et al., 2017). In due course, greater exposure of lake ecosystems to severe heat may lead to the permanent loss of species, similar to what has already been seen in ocean environments due to the escalating occurrence of marine heatwaves (Cheung et al., 2021; Smale et al., 2019; Straub et al., 2019; Woolway, et al., 2022).

Water temperature, dissolved oxygen, conductivity, water mixing, nutrients, organic matter content, among others, are some of the factors that influence the formation and composition of phytoplankton (Hardikar et al., 2017; Wang et al., 2015). The dominance, biomass, and community structure of phytoplankton are greatly altered with a change in water temperature (Rasconi et al., 2015). Water temperature is thus considered as a key environmental element in shaping phytoplankton communities (Tian et al., 2013). Aside from its influence on vertical mixing and introduction of nutrients into the surface layer, temperature also directly stimulates the development of phytoplankton through metabolic processes (Fernández-González et al., 2022). Considering its influence on phytoplankton metabolism, an increase in temperature may potentially lead to either an increase or decrease in its biomass, which could impact the richness and evenness of phytoplankton (Boyce et al., 2010). Consequently, the impact of

temperature can vary among different groups of phytoplankton, even within a single species, based on abiotic factors (Butterwick et al., 2005; Fernández-González et al., 2022). The dissolved oxygen concentration in aquatic ecosystems is crucial in preserving the variety of microorganisms as well as sustaining ecological and biogeochemical functions. The existence of aquatic organisms, phytoplankton, zooplankton and aquatic plants, depends on the waterbody having adequate oxygen levels (Zhao et al., 2021). Conductivity is a fundamental metric of the chemical and biological state of an aquatic ecosystem (Dumelle et al., 2024). Conductivity serves as a vital indicator of the total dissolved constituents in water, reflecting the concentration of various ions and minerals. The critical significance of these environmental variables cannot be overstated, as they are increasingly impacted by climate change (Kasprzak et al., 2017). Furthermore, the interplay between these variables and hydrological conditions plays a pivotal role in shaping biological distribution within aquatic ecosystems (Ahmed et al., 2021).

With global temperatures projected to continue to increase (Kasprzak et al., 2017), it is expected that regional aquatic systems will experience gradual changes in water temperature, dissolved oxygen, and conductivity and, subsequently, the quantity and composition of phytoplankton. Studies have indicated that global lake temperatures increased at a rate of 0.34 °C per decade from 1985 to 2009. Notably, freezing lakes exhibit a warming trend approximately twice that of the global average (O'Reilly et al., 2015; Woolway et al., 2022). Woolway & Maberly (2020) and Grant et al. (2021) predicted that by the close of the 21st century, global mean water temperatures could increase by an additional 1 - 4 °C and will challenge many freshwater species in locating appropriate thermal habitats (Kraemer et al., 2021). Lakes respond very differently to global warming, depending on the type of lake and its catchment area. For instance, in lakes that experience seasonal stratification, like dimictic and monomictic lakes,

warmer winters may cause stratification to begin earlier in the spring and persist later into the fall. This alteration leads to an extended growing season (Leibniz-Institute of Freshwater Ecology and Inland Fisheries, 2018). This stratification and cycling impact various processes such as oxygen distribution, nutrient exchange, microbial activity and ecosystem evolution (Alexakis et al., 2013; Robertson & Ragotzkie, 1990; Zhang et al., 2015). Prolonged thermal stratification can affect hypolimnetic nutrient concentrations, which in turn can influence phytoplankton populations (Lavoie & Auclair, 2012; Lindstrom, 2004). It is therefore essential to understand the past and present condition of the aquatic ecosystem to make informed management decisions.

A confounding factor is the occurrence and timing of major storms. Given the location of Lake Louise in a hurricane-prone region, it is expected that major storms would have an influence on the ecosystem. Indeed, Miller et al. (2006), through isotopic analysis of the cellulose in tree rings, were able to reconstruct a 220-year record of the major storms, including the Great Hurricane season of 1780 with 3 major Atlantic storms, impacting the vicinity of Lake Louise. In addition, the numbers and intensities of tropical storms and hurricanes have increased in the North Atlantic since the 1980s (Murakami et al., 2020). Unfortunately, it is expected that storms will generally become more frequent, intense, and longer in duration (Bacmeister et al., 2018). While it is tempting to attribute the increase in numbers to anthropogenic climate change, it may be more directly related to multidecadal climate oscillations in the Atlantic (Knutson et al., 2020). Regardless of the cause, the increase in numbers and intensities could still have a significant impact on regional and aquatic ecosystems, especially when tied to increasing temperatures. It is also known that major storms can disrupt behavior of aquatic ecosystems and reshape microbial communities in aquatic systems in the short-term (Garrison et al., 2022; Gould et al., 2019; James et al., 2008; LaMontagne et al., 2022). Alterations in the abiotic conditions of

lakes caused by storms, along with the physical movement of phytoplankton throughout the water column, may influence how phytoplankton species compete with each other, thereby affecting community dynamics (Huisman et al., 2004; Smith, 1983). Sudden rises in lake water levels caused by an intense rainfall event can inundate already exposed lake beds, affecting the shoreline, which then leads to a rippling effect on phytoplankton (Jeppesen et al., 2015; Zohary & Ostrovsky, 2011). The degree to which long-term storm events could impact phytoplankton populations are less clear.

With this in mind, an opportunity was taken from the passage of Hurricane Idalia through the region to examine the long-term impacts of a major hurricane on Lake Louise, Georgia. On August 30, 2023, the center of Idalia passed within 25 km of Lake Louise bringing with it maximum sustained winds of 40 meters per second (Montgomery & Walker, 2024; National Weather Service, 2025a), much stronger than the 25 m/s winds associated with Hurricane Irma (National Weather Service, 2019); the short-term effects of Hurricane Irma were reported on by Gould et al. (2019). Once access to the lake was restored in January, 2024, we began a bi-weekly monitoring program to see if the seasonal progression of conditions in Lake Louise had been significantly altered by Hurricane Idalia.

During the course of our investigation, Lake Louise was impacted by three additional hurricanes. After making landfall along the coast of Taylor County in Florida on August 5, 2024, the remnants of Hurricane Debby passed near Valdosta with maximum sustained winds of 19.5 m/s, maximum gusts of 25.7 m/s, bringing with it 14 – 18 cm of rainfall. Hurricane Helene made landfall on September 26, 2024, also in Taylor County, Florida, passed over Valdosta later that day with sustained winds of 27 m/s and maximum wind gusts in excess of 43 m/s in the vicinity of Lake Louise, bringing about 9.5 cm of rain to the area, (NOAA, 2025). The lake also

felt the effects of Hurricane Rafael in early November, 2024; Rafael did not make landfall but brought heavy rains to the region, up to 16.5 cm in less than 24 hours, 26 cm in 48 hours (National Weather Service 2025b).

In this study, environmental variables including water temperature, conductivity and dissolved oxygen were measured between January 27, 2024, and January 17, 2025. These were compared with archived data collected between January 3, 2003, and December 13, 2003, between January 17, 2004, and December 11, 2004, and between February 10, 2017, and December 9, 2017, in order to determine the possible presence of interannual trends and the impacts of major storms. Additionally, water samples were also collected to assess changes in chlorophyll concentrations and in the phytoplankton association in relation to the environmental variables. The primary objective of the study was to re-establish a baseline for Lake Louise with an emphasis on the phototrophic community after Hurricane Idalia. It was hypothesized that changes in seasons influence phytoplankton community composition in Lake Louise, and that the phytoplankton community will return to its pre-disturbance state.

CHAPTER II

MATERIALS AND METHODS

Lake Louise Description

Lake Louise lies about 15 km south of Valdosta, Georgia, USA (coordinates: 30° 43.5' N and 83° 15.5' W; Figure 1) and is an integral part of the Valdosta State University-maintained Lake Louise Field Station (Riggs et al., 2010). The station covers an estimated area of 76.9 ha. The vegetation at the station creates a forested environment that protects the lake from surface winds (Riggs et al., 2010).

The lake is 5.7 hectares in area, with a depth of 6.4 m at its deepest point (Tepper & Hyatt, 2011). The lake was formed approximately 9,500 years ago when the underlying limestone dissolved and the surface collapsed, creating a large sinkhole, the lake (Tepper & Hyatt, 2011). Today, Lake Louise is primarily fed by precipitation and seepage from nearby soils (Tepper & Hyatt, 2011). Organic-rich soils nearby stain the lake water with tannic acid and humic substances, giving it a dark color (Tepper & Hyatt, 2011). During the summer, the hypolimnion stays below 16 °C, while the epilimnion can reach temperatures of over 30 °C (Gould et al., 2019). The lake is stratified from March to November, but mixes several times during the winter based on weather patterns (Gould et al., 2019; Tepper & Hyatt, 2011).

Environmental Monitoring

Water samples were collected from the lake biweekly between January, 2024 and January, 2025 between 10:00 a.m. and noon to avoid potential for diel fluctuations of variables. Water samples (1.5 L) were collected from the lake at depths of 0 m, 1 m, 2 m, 3 m, 4 m and 5 m with Kemmerer bottles. The collected samples were transported to the laboratory for further analysis. Environmental variables such as water temperature ($^{\circ}\text{C}$), dissolved oxygen (DO) (mg/L), and specific conductivity (mS/cm) were measured in-situ at the deepest point in the lake, marked by a PVC pipe, and logged at 10-centimeter intervals to a depth of between 5.5 and 6 meters, depending on the water level. The water temperature and conductivity were measured using a YSI Pro2030 Meter while the dissolved oxygen was measured using YSI EXO1 Multiparameter sonde attached to an EXO hand-held display (YSI, Inc., Yellow Springs, Ohio). Relative water level was monitored using a scale marked in 2-cm intervals fixed to a wooden post on the edge of the lake. Archived data collected using similar techniques from January 3, 2003, to December 13, 2003, from January 17, 2004, to December 11, 2004, and from February 10, 2017, to December 9, 2017, were used for comparison. 2003 and 2004 were not impacted by major storms, but Hurricane Irma affected the area in September 2017. Conductivity data was not available for 2003 and 2004.

Pigment Analysis

Chlorophyll *a* was measured from the water samples collected at 1-meter intervals from the surface to a depth of 5 meters. This pigment analysis followed the procedure of Gould et al. (2019). Pigment analysis provides a reasonably accurate way to quantify the weight and volume of phytoplankton in waterbodies. It also serves as an empirical link between nutrient

concentration and several significant biological phenomena (Carlson & Simpson, 1996). To prepare for testing, and depending on the density of microorganisms in the sample, 3 100 – 250-mL aliquots of the whole water samples were filtered onto glass fiber filters with a nominal pore size of 0.7 μm . Once filtered, they were extracted overnight in 90% acetone at 4 °C. The extracted samples were spun at high speed in a centrifuge and the supernatant analyzed using a PerkinElmer Lambda 35 UV/VIS spectrometer by scanning between 350 nm and 800 nm against a 90% acetone blank. The concentration of chlorophyll *a* ($\mu\text{g/L}$) was determined from the spectra following the trichroic equation of Jeffrey & Humphrey (1975). The equation is given as: Chlorophyll *a* = $11.85 \cdot (A_{664} - A_{750}) - 1.54 \cdot (A_{647} - A_{750}) - 0.08 \cdot (A_{630} - A_{750})$ Archived samples and data collected with similar procedures from February 17, 2017 to December 9, 2017, from January 17, 2004 to December 11, 2004, and from January 3, 2003 to December 13, 2003, were used for comparison.

Phytoplankton Collection and Identification with Flow Cytometry and Light Microscopy

To quantify the phytoplankton association, we collected 50 mL of unfiltered water samples at 1-meter intervals from the surface to a depth of 5 meters. The water samples were immediately fixed with 1 mL of Lugol's iodine and returned to the laboratory. To aid in identification, a vertical plankton tow using a 25- μm plankton net was also collected; these were returned to the laboratory unfixed. Net plankton samples were observed using an Olympus BX60 microscope equipped with differential interference contrast optics (Olympus, Tokyo, Japan) and a Canon EOS Rebel digital camera (Canon, Tokyo, Japan) configured for remote viewing using the Canon EOS Utilities package. Phytoplankton in the unfiltered water samples was quantified using a FlowCAM[®] (Fluid Imaging Technologies, Scarborough, Maine) imaging flow cytometer using 10x objective lens. A 3-mL aliquot of each sample was pre-filtered using a 64- μm

membrane filter to eliminate large debris and ensure that the particles were within suitable ranges for analysis. A 1-mL aliquot of the filtered material was then analyzed with the FlowCAM[®]. Optical filters were created for each sample using the Visual Spreadsheet Software accompanying the instrument; the optical filters were used to classify the images on the basis of their size, shape and color, and estimate the numbers of each type. FlowCAM[®]-generated images were compared with light micrographs of net phytoplankton samples collected from the lake to validate the types of phytoplankton associated with each optical filter. Archived samples and data collected with similar procedures from February 6, 2017, to October 21, 2017, were used for comparison.

Statistical Analysis

All statistics were performed using the R software packages (R Core Team 2024). The maximum, minimum, mean and standard deviation for the environmental variables across the period were calculated. To check for normality in the data, the distribution of each environmental variable was checked with the Shapiro-Wilk normality test (Royston, 1982) using the `Shapiro.test` function, after which a Kruskal-Wallis test and a Dunn's multiple comparison test (Dunn, 1964) using the `dunn.test` and `FSA` packages were done. Significant differences between the seasons were measured at the $\alpha = 0.05$ level; seasonal periods were defined as follows: spring (March – May), summer (June – August), fall (September – November), and winter (December – February). Additionally, the Modified Mann-Kendall trend test was performed (Hamed & Rao, 1998) for water temperature, dissolved oxygen and conductivity at the seasonal scale and entire lake using the modified `mk` package in R, tested at $\alpha = 0.05$ significance level. Cyanobacteria counts were examined to know if they were the most abundant among the phytoplankton groups obtained from the optical filters in 2017 and 2024 by performing the Wilcoxon rank-sum test

(Bauer, 1972) using the `wilcox.test` function in R. A more in-depth analysis of the influence of water temperature, conductivity, and dissolved oxygen levels on structuring of the phytoplankton community in Lake Louise was conducted by using Permutational Multivariate Analysis of Variance (PERMANOVA) following the Bray-Curtis dissimilarity, 999 permutations. Graphs were generated using `ggplot2` in R.

CHAPTER III

RESULTS

Environmental Variables

Water Temperature

The seasonal variation in temperature during the four monitoring periods – January 27, 2024 to January 17, 2025, February 10, 2017, to December 9, 2017, January 17, 2004, to December 11, 2004, and January 3, 2003, to December 13, 2003 – is presented in Figures 2, 3, 4 and 5, respectively. In all four years, thermal stratification began in early March, becoming fully established by late April, and continued until early November. After stratification, temperatures in the epilimnion/upper thermocline region varied between 22 °C and 30 °C in 2024 (Figure 2), between 24 °C and 30 °C in both 2017 and 2004 (Figures 3 & 4), and between 22 °C and 28 °C in 2003 (Figure 5). Temperatures in the hypolimnion gradually warmed from a winter minimum, but generally remained 10 °C lower than the epilimnion. In 2024, the lowest and highest water temperatures were recorded in February (11.1 °C) and July (29.8 °C), respectively, with a mean temperature of 17.1 °C (± 3.6 °C). In 2017, the lake had a mean water temperature of 18.5 °C (± 3.5 °C), with the lowest temperature (13.1 °C) recorded in February and the highest (30.4 °C) in July. In 2004, the mean water temperature in the lake was 19.3 °C (± 3.4 °C) with the lowest temperature (10.2 °C) recorded in January and the highest (29.8 °C) in July, 2004. In 2003, the

mean water temperature was 18.7 °C (\pm 3.7 °C), with the lowest temperature (9.3 °C) recorded in February and the highest (29.4 °C) in August (Table 1).

Month	Temp (°C) 2024				Temp (°C) 2017				Temp (°C) 2004				Temp (°C) 2003			
	Mean	Max	Min	SD \pm	Mean	Max	Min	SD \pm	Mean	Max	Min	SD \pm	Mean	Max	Min	SD \pm
Jan	12.0	15.1	11.3	1.1	*	*	*	*	10.7	11.4	10.2	0.5	11.0	12.1	10.3	0.7
Feb	12.4	15.9	11.1	1.5	14.2	17.8	13.1	1.6	11.2	12.1	10.7	0.4	11.3	13.1	9.3	1.3
Mar	13.9	18.8	11.3	2.9	14.5	17.5	13.2	1.5	15.4	19.3	10.9	3.0	16.1	20.0	10.0	3.7
Apr	15.3	21.6	11.7	3.7	16.7	24.4	13.4	3.9	18.1	22.7	11.1	4.1	16.7	19.9	10.5	3.4
May	17.4	25.4	12.3	5.1	18.4	26.6	13.6	5.0	20.9	26.0	11.4	5.4	21.0	28.3	11.0	6.1
Jun	18.9	29.3	12.7	6.4	20.0	29.0	13.9	5.7	24.5	29.5	12.0	6.6	22.2	27.8	11.5	6.0
Jul	20.4	29.8	13.3	6.5	21.0	30.4	14.2	6.0	25.5	29.8	12.8	6.2	23.1	28.4	12.0	5.9
Aug	20.6	28.2	13.9	5.3	21.8	30.2	14.7	5.9	24.9	29.6	13.3	5.2	24.2	29.4	12.5	6.0
Sep	20.5	26.6	14.3	4.8	21.3	27.4	15.2	4.3	24.6	27.6	14.0	4.5	23.3	26.3	13.1	4.6
Oct	19.6	22.7	15.0	2.8	20.9	25.4	15.8	3.3	21.5	23.5	14.6	2.4	*	*	*	*
Nov	19.1	22.0	15.8	2.0	17.8	18.9	16.3	0.6	17.9	20.0	15.4	1.4	19.0	21.2	14.0	2.0
Dec	14.1	15.3	13.8	0.5	16.2	17.5	15.9	0.5	16.3	17.6	15.1	1.0	17.4	18.6	14.5	1.1
Lake	17.0	29.8	11.1	3.5	18.5	30.4	13.1	3.5	19.3	29.8	10.2	3.4	18.7	29.4	9.3	3.7

*=*data not available*

Conductivity

Figures 6 and 7 illustrate the variation in the lake’s conductivity during the monitoring periods January 27, 2024, to January 17, 2025, and February 10, 2017, to December 9, 2017, respectively. Between late April and November during both years, ion concentrations in the hypolimnion increased as stratification of the lake stabilized (Figures 6 & 7). The month of October in 2024 showed the greatest variation in conductivity, ranging from near 0.035 at the surface to 0.125 mS/cm near the bottom of the lake. The mean conductivity was 0.055 mS/cm (\pm 0.009 mS/cm) (Figure 6). In 2017, the mean conductivity was 0.052 mS/cm (\pm 0.008 mS/cm)

which varied between 0.038 mS/cm in June and August, and 0.140 mS/cm in November (Table 2).

Table 2: Summary statistics of conductivity measured in Lake Louise for 2024 and 2017.

Month	Cond (mS/cm) 2024				Cond (mS/cm) 2017			
	Mean	Max	Min	SD (\pm)	Mean	Max	Min	SD (\pm)
Jan	0.047	0.047	0.046	0.000	*	*	*	*
Feb	0.044	0.048	0.039	0.002	0.046	0.063	0.041	0.007
Mar	0.048	0.056	0.042	0.005	0.047	0.066	0.041	0.008
Apr	0.049	0.061	0.039	0.008	0.049	0.082	0.042	0.011
May	0.053	0.073	0.037	0.012	0.050	0.097	0.041	0.016
Jun	0.056	0.078	0.038	0.013	0.049	0.100	0.038	0.018
Jul	0.057	0.089	0.035	0.017	0.052	0.113	0.039	0.021
Aug	0.057	0.096	0.038	0.018	0.052	0.118	0.038	0.024
Sep	0.062	0.103	0.039	0.020	0.055	0.130	0.042	0.025
Oct	0.064	0.125	0.044	0.026	0.056	0.136	0.042	0.026
Nov	0.066	0.124	0.042	0.027	0.060	0.140	0.052	0.022
Dec	0.053	0.069	0.049	0.005	0.056	0.063	0.050	0.002
Lake	0.055	0.125	0.035	0.009	0.052	0.140	0.038	0.008

* Data not available

Dissolved Oxygen

Figures 8, 9, 10 and 11 show the variation in dissolved oxygen during all of the monitoring periods: January 27, 2024, to January 17, 2025, February 10, 2017, to December 09, 2017, January 17, 2004, to December 11, 2004, and January 3, 2003, to December 13, 2003, respectively. During all monitoring periods, dissolved oxygen was quite uniform through the water column between January and March with the exception of 2017, when early thermal stratification was disrupted by a cold snap (compare Fig. 9 with Fig. 3). After stratification, oxygen was confined to the epilimnion; the deeper waters remained oxygen-deprived even when the thermal gradient disappeared. Anoxic conditions were apparent below 2 m depth (Figures 8,

9, 10 & 11). In 2024, March showed the greatest variation in DO in the lake, with a maximum concentration of 9.4 mg/L at the surface and a minimum of 3.3 mg/L near the bottom. The minimum oxygen concentration recorded was 0.02 mg/L in November. The mean DO was 2.01 mg/L (\pm 1.70 mg/L). In 2017, the mean DO was 2.0 mg/L (\pm 2.6 mg/L) with a minimum DO of 0.1 mg/L recorded in February, May, July, August and September, and a maximum of 10.9 mg/L recorded in February. The mean DO in 2004 was 4.1 mg/L (\pm 2.8 mg/L) with a minimum of 0.4 mg/L in April, May, June, July and August, and a maximum DO of 12.1 mg/L recorded in March. In 2003, the lake's mean DO was 4.0 mg/L (\pm 2.2 mg/L) which was between 0.3 mg/L in August and September, and 10.7 mg/L in February (Table 3).

Table 3: Summary statistics of dissolved oxygen in Lake Louise for 2024, 2017, 2004 and 2003.

Month	DO (mg/L) 2024				DO (mg/L) 2017				DO (mg/L) 2004				DO (mg/L) 2003			
	Mean	Max	Min	SD \pm	Mean	Max	Min	SD \pm	Mean	Max	Min	SD \pm	Mean	Max	Min	SD \pm
Jan	5.66	7.21	4.60	0.84	*	*	*	*	5.6	7.4	4.2	\pm 1.2	7.9	8.6	7.2	0.5
Feb	*	*	*	*	2.9	10.9	0.1	4.0	6.7	8.4	3.3	\pm 1.8	9.2	10.7	6.2	1.7
Mar	4.99	9.40	3.30	2.36	2.9	9.9	0.2	3.3	6.1	12.1	1.2	\pm 4.4	5.0	9.5	0.6	3.3
Apr	1.86	7.04	0.14	2.44	1.5	7.8	0.2	2.6	5.2	10.3	0.4	\pm 4.2	3.3	7.0	0.4	2.4
May	1.24	4.56	0.03	1.56	1.6	5.9	0.1	2.3	3.8	8.3	0.4	\pm 3.5	2.6	8.1	0.4	3.0
Jun	1.50	6.91	0.07	1.98	1.7	7.9	0.3	2.5	4.1	8.2	0.4	\pm 3.3	2.7	7.3	0.4	2.8
Jul	1.82	7.57	0.15	2.28	1.5	7.7	0.1	2.7	3.6	7.9	0.4	\pm 3.2	2.4	6.9	0.4	2.6
Aug	1.30	5.90	0.04	1.85	1.9	8.0	0.1	3.1	2.9	10.0	0.4	\pm 3.6	2.2	6.7	0.3	2.5
Sep	0.87	5.03	0.09	1.20	1.6	8.0	0.1	2.4	2.6	5.3	0.6	\pm 1.8	2.6	5.8	0.3	2.3
Oct	0.69	3.02	0.04	0.76	2.4	9.0	0.2	3.0	2.9	5.8	0.5	\pm 1.6	*	*	*	*
Nov	0.80	4.35	0.02	1.13	1.3	5.0	0.3	1.1	2.0	5.2	0.5	\pm 1.9	2.8	5.7	0.5	1.5
Dec	1.33	6.82	0.10	1.85	2.3	6.8	1.5	1.4	3.5	8.4	0.6	\pm 3.5	3.0	5.2	0.5	1.1
Lake	2.01	9.40	0.02	1.70	2.0	10.9	0.1	2.6	4.1	12.1	0.4	\pm 2.8	4.0	10.7	0.3	2.2

**Data not available*

Figure 12 presents the seasonal differences in water temperature, conductivity and dissolved oxygen for 2024, 2017, 2004 and 2003. Seasonal periods were defined as follows: spring (March – May), summer (June – August), fall (September – November), and winter (December – February). The results of the Shapiro-Wilk normality showed that the data were generally not normally distributed. Therefore, we compared the environmental variables across seasons and years using a Kruskal-Wallis test at $\alpha = 0.05$ significance level. The findings indicated differences in the mean ranks of seasonal water temperature, conductivity and dissolved oxygen measured (Table 4), consistent with the variances revealed in the fall, winter, spring and summer box-plots (Figure 12). For the 2024 variables measured, pairwise comparison from Dunn's test for water temperature and oxygen revealed significant differences between fall-spring, spring-summer, fall-winter, spring-winter and summer-winter ($p < 0.05$); only the fall-summer comparison was not significantly different ($p > 0.05$). Regarding the lake's conductivity, significant difference was only observed between fall-spring ($p = 0.02$), and fall-winter ($p = 0.01$). In 2017, water temperature revealed significant differences between fall-spring, spring-summer, fall-winter and summer-winter ($p < 0.05$), but not for fall-summer ($p = 1.00$) and spring-winter ($p = 1.00$). For conductivity, there was significant difference between fall-spring ($p < 0.05$) and spring-summer ($p < 0.05$) but not for fall-summer ($p = 1.00$), spring-winter ($p = 0.08$), fall-winter ($p = 1.00$) and summer-winter ($p = 0.64$). Regarding the lake's oxygen, significant difference was found between fall-summer, fall-winter, spring-winter and summer-winter ($p < 0.05$) except for fall-spring ($p = 1.00$) and spring-summer ($p = 0.11$) that were not significantly different. The water temperature in 2004, showed significant differences between fall-spring, spring-summer, fall-winter, spring-winter and summer-winter ($p < 0.05$) except for fall-summer ($p = 0.52$). The lake's oxygen showed significant difference between fall-winter

only ($p < 0.05$) except for fall-spring ($p = 0.10$), fall-summer ($p = 1.00$), spring-summer ($p = 0.36$), spring-winter ($p = 1.00$) and summer-winter ($p = 0.07$) that were not significantly different. The pairwise comparison of water temperature in 2003 revealed significant differences between fall-spring, spring-summer, fall-winter, spring-winter and summer-winter seasons ($p < 0.05$) except for fall-summer ($p = 0.33$). Concerning the lake's oxygen, significant differences were found between fall-winter ($p < 0.05$), spring-winter ($p = 0.01$) and summer-winter ($p < 0.05$), but not for fall-spring ($p = 0.87$), fall-summer ($p = 1.00$), and spring-summer ($p = 0.16$) (Table 5).

Table 4: Kruskal-Wallis (H) test for comparison of environmental variables over time.

2024				2017			
Variable	H	df	<i>p</i> -value	Variable	H	df	<i>p</i> -value
Temperature	106.08	3	*	Temperature	75.50	3	*
Conductivity	14.14	3	*	Conductivity	18.23	3	*
Oxygen	100.44	3	*	Oxygen	42.62	3	*
2004				2003			
Variable	H	df	<i>p</i> -value	Variable	H	df	<i>p</i> -value
Temperature	63.50	3	*	Temperature	50.85	3	*
Oxygen	12.80	3	0.01	Oxygen	34.76	3	*

* $p < 0.001$

Table 5: Dunn's pairwise comparison test for water temperature, conductivity and dissolved oxygen.

Comparison	Temperature (°C) 2024			Conductivity (mS/cm) 2024			DO (mg/L) 2024		
	z	<i>p</i> -unadj	<i>p</i> -adj	z	<i>p</i> -unadj	<i>p</i> -adj	z	<i>p</i> -unadj	<i>p</i> -adj
Fall-Spring	6.00	*	*	2.88	0.00	0.02	-6.18	*	*
Fall-Summer	0.87	0.38	1.00	1.27	0.21	1.00	-2.11	0.04	0.21
Spring-Summer	-5.14	*	*	-1.62	0.11	0.63	4.07	*	*
Fall-Winter	8.82	*	*	3.35	0.00	0.01	-9.14	*	*
Spring-Winter	2.82	0.00	0.03	0.46	0.65	1.00	-2.96	0.00	0.02
Summer-Winter	7.95	*	*	2.08	0.04	0.23	-7.03	*	*
2017									
Fall-Spring	6.17	*	*	3.07	0.00	0.01	0.79	0.43	1.00
Fall-Summer	0.97	0.33	1.00	-1.03	0.30	1.00	3.14	0.00	0.01
Spring-Summer	-5.20	*	*	-4.10	0.00	0.00	2.35	0.02	0.11
Fall-Winter	6.96	*	*	0.58	0.56	1.00	-3.31	0.00	0.01
Spring-Winter	0.80	0.43	1.00	-2.49	0.01	0.08	-4.10	*	0.00
Summer-Winter	5.99	*	*	1.61	0.11	0.64	-6.44	*	*
2004									
	Temperature			Oxygen					
Fall-Spring	2.68	0.01	0.04	-2.38	0.02	0.10			
Fall-Summer	-1.71	0.09	0.52	-0.50	0.62	1.00			
Spring-Summer	-4.39	*	*	1.88	0.06	0.36			
Fall-Winter	5.74	*	*	-3.04	0.00	0.01			
Spring-Winter	3.06	0.00	0.01	-0.66	0.51	1.00			
Summer-Winter	7.45	*	*	-2.54	0.01	0.07			
2003									
Fall-Spring	2.85	0.00	0.03	-1.456	0.15	0.87			
Fall-Summer	-0.97	0.33	1.00	0.76	0.45	1.00			
Spring-Summer	-3.82	*	0.00	2.21	0.03	0.16			
Fall-Winter	5.46	*	*	-4.68	*	*			
Spring-Winter	2.61	0.01	0.05	-3.23	0.00	0.01			
Summer-Winter	6.43	*	*	-5.44	*	*			

**p* < 0.001; *p*-unadj = *p* unadjusted; *p*-adj = *p* adjusted

To compare the trends in water temperature, conductivity and dissolved oxygen during the monitoring periods in 2024, 2017, 2004 and 2003, the Modified Mann-Kendall test was

employed (Table 6). The trends in the lake's water temperature over the four years showed declining temperatures across all seasons, which were statistically significant, though the magnitude of decline varied. These were reflected by their Sen's slope which decreased by -0.07 °C in spring, -0.06 °C in summer, and -0.03 °C in both fall and winter in 2024. In 2017, the decrease in Sen's slope were -0.17 °C in spring, -0.33 °C in summer and -0.16 °C in fall and -0.04 °C in winter. In 2004, Sen's slope decreased by -0.40 °C in spring, -0.40 °C in summer, and -0.16 °C in fall and -0.07 °C in winter whereas in 2003, decline in Sen's slope were -0.45 °C in spring, -0.60 °C in summer, and -0.19 °C in fall and -0.10 °C in winter. Conductivity in 2024 and 2017 showed significant increasing trend in all seasons, with considerably lower magnitudes. The trends in oxygen over the four years showed significant decreasing oxygen in all seasons with respective declines in Sen's slope by about -0.07 mg/L, -0.06 mg/L, -0.03 mg/L and -0.05 mg/L in spring summer, fall and winter respectively in 2024, -0.05 mg/L, -0.01 mg/L, -0.07 mg/L and -0.07 mg/L in spring, summer, fall and winter respectively in 2017, -0.47 mg/L, -0.39 mg/L, -0.20 mg/L and -0.26 mg/L in spring, summer, fall and winter respectively in 2004 and by about -0.33 mg/L, -0.27 mg/L, -0.22 mg/L and -0.10 mg/L in spring, summer, fall and winter respectively in 2003. For the entire lake (annual), water temperature showed non-significantly increasing trend in 2024 (Sen's slope = 0.75 °C/yr), 2017 (Sen's slope = 0.50 °C/yr) and 2004 (Sen's slope = 0.81 °C/yr) but a significantly increasing trend in 2003 (Sen's slope = 1.05 °C/yr). Conductivity showed significant increasing trends (Sen's slope = 0.002 mS/cm/yr) in 2024 and in 2017 (Sen's slope = 0.001 mS/cm/yr). Oxygen in the lake recorded a significant decreasing trend (Sen's slope = -0.2 mg/L/yr) in 2024, 2004 (Sen's slope = -0.38 mg/L /yr) and in 2003

(Sen's slope = -0.30 mg/L/yr) but a non-significant decreasing trend (Sen's slope = -0.05 mg/L/yr) in 2017 (Table 6).

Table 6: Trends in water temperature, conductivity and dissolved oxygen of Lake Louise.

Class	Temperature (°C) 2024			Cond (mS/cm) 2024			Oxygen (mg/L) 2024		
	Zc	p-value	Slope	Zc	p-value	Slope	Zc	p-value	Slope
Spring	-3.82	*	-0.07	4.34	*	0.001	-3.82	*	-0.07
Summer	-3.90	*	-0.06	5.64	*	0.001	-3.90	*	-0.06
Fall	-3.80	*	-0.03	3.89	*	0.001	-3.80	*	-0.03
Winter	-3.75	0.00	-0.03	4.97	*	0.000	-3.36	0.00	-0.05
Annual	1.65	0.10	0.79	3.38	0.00	0.002	-2.65	0.01	-0.20
2017									
Spring	-4.07	*	-0.17	10.35	*	0.002	-3.86	*	-0.05
Summer	-4.53	*	-0.33	6.03	*	0.002	-3.20	0.00	-0.01
Fall	-4.81	*	-0.16	3.91	*	0.000	-3.84	0.00	-0.07
Winter	-3.47	0.00	-0.04	5.42	*	0.000	-3.90	0.00	-0.07
Annual	1.01	0.31	0.50	3.69	*	0.001	-0.55	0.58	-0.05
2004									
Class	Temperature			Oxygen					
	Zc	p-value	Slope	Zc	p-value	Slope			
Spring	-3.68	0.00	-0.40	-4.55	*	-0.47			
Summer	-3.94	*	-0.40	-4.12	*	-0.39			
Fall	-3.67	0.00	-0.16	-4.11	*	-0.20			
Winter	-4.33	0.00	-0.07	-4.15	*	-0.26			
Annual	1.06	0.29	0.81	-3.30	0.00	-0.38			
2003									
Spring	-3.99	*	-0.45	-3.78	*	-0.33			
Summer	-3.91	*	-0.60	-3.78	*	-0.27			
Fall	-4.05	*	-0.19	-4.37	*	-0.22			
Winter	-4.71	*	-0.10	-4.02	*	-0.10			
Annual	2.34	0.02	1.05	-1.29	0.20	-0.30			

* $p < 0.001$

From the results (Table 6), spring 2003 showed the steepest decline in the lake's water temperature by magnitude followed by 2004, 2017 and the mildest magnitude being 2024. Similar pattern was observed for summer, fall and winter. Generally, the steepest decline in water temperature was recorded in the summer, and the least in the winter. Conductivity exhibited a similar increasing trend, with the magnitude of increase during the summer and spring of 2017 exceeding that observed in 2024. In contrast, during the fall, the magnitude of increase was greater in 2024 than in 2017, while in winter, both years demonstrated comparable increases. The reduction in dissolved oxygen levels in the lake exhibited the most significant declines during the spring season compared to summer, fall, and winter across all observed years. Spring 2004 recorded the most pronounced decrease, followed by spring 2003, spring 2024, and the least decline noted in spring 2017. A comparable trend was also observed in the summer months across all years. In the fall season, the peak decline in dissolved oxygen was observed in 2003 with subsequent decreases noted in 2004, 2017 and 2024. Conversely, the winter of 2004 recorded the most pronounced oxygen depletion followed by declines in 2003, 2017 and the least reduction in 2017. These findings underscore the consistent patterns in water temperature, conductivity, and dissolved oxygen across the examined years in Lake Louise.

Water Level

A plot of the relative water level is given in Figure 13. There are clear peaks related to the passages of hurricanes Debby and Rafael, both cases indicating a rise in the water level of 15 to 20 cm. The absence of a corresponding peak in connection with Hurricane Helene may reflect the fact that we were unable to access the lake for 10 days after the hurricane moved through.

Chlorophyll *a* Profile in Lake Louise

The concentration of chlorophyll *a* (Chl-*a*) in lake Louise from January 3, 2003 to December 13, 2003, from January 17, 2004 to December 11, 2004, from February 17, 2017 to December 9, 2017 and from January 27, 2024 to January 17, 2025 are shown in Figures 14, 15, 16 & 17 respectively. Chlorophyll-*a* concentrations exhibited a pronounced bloom starting in late February and persisted through November across all four years of observation. Elevated levels were consistently recorded in the epilimnion and the vertically mixed water column of the lake. One day following Hurricane Debby's passage in early August, chlorophyll *a* concentration in the epilimnion ranged from 100 µg/L to 125 µg/L. This concentration experienced a decline after Hurricane Helene made landfall in late September. Conversely, a notable increase in chlorophyll *a* was observed in the epilimnion 1-5 days post-Hurricane Irma's passage, continuing to rise until mid-October 2017 (100 µg/L – 250 µg/L).

Phytoplankton Counts in Lake Louise

The phytoplankton count in Lake Louise from February 6 to October 21, 2017, and January 27 to December 20, 2024, are presented in Figures 18 & 19, respectively. During both monitoring periods, the phytoplankton was composed of chlorophytes, chrysophytes, cyanobacteria, dinoflagellates, euglenophytes and raphidophytes. In 2017, an increase in the abundance of cyanobacteria throughout the spring, summer, and fall was observed, especially about four weeks after the passage of Hurricane Irma in 2017. However, during the monitoring period in 2024, there was a general decrease in the abundance of cyanobacteria throughout the water column, but especially in August (before and after the passage of Hurricane Debby) and September (before and after the passage of Hurricane Helene). The Wilcoxon rank-sum test for 2017 count revealed a test statistic (W) = 240597 and a p -value $< 2.2 \times 10^{-16}$ whereas in 2024, test

statistic (W) = 119925 and p -value = 0.1257 was recorded. The results of the counts indicate that in 2017, cyanobacteria were significantly more abundant, i.e. their median count was greater than the median count of chlorophytes, chrysophytes, dinoflagellates, euglenophytes and raphidophytes. However, it was lower in 2024 (Figure 20). Figure 21 shows the comparison between FlowCAM-generated images and light micrographs of net phytoplankton samples.

Influence of Depth and Environmental Variables on Phytoplankton

The PERMANOVA result for phytoplankton community and environmental variables (water temperature, conductivity and dissolved oxygen) in Lake Louise is presented in Table 7. The findings indicate that water temperature, conductivity and dissolved oxygen exerted substantial influence on the phytoplankton community ($p = 0.001$). Water temperature accounted for 65.66% of the observed variation, showing that fluctuations in water temperature played a crucial role in shaping the phytoplankton association. Conductivity, though exhibited a significant influence, had a considerably little impact and accounted for only 7.88% of the variation in the phytoplankton association. Dissolved oxygen likewise contributed 23.20% of the variation observed. Additionally, the residual variance was measured at 3.257% which suggests that while these essential factors are influential, there are other variables contributing to the phytoplankton community dynamics in Lake Louise.

Table 7: PERMANOVA Result for Environmental Variables (2017 & 2024) in Lake Louise.

	Df	SumOfSqs	R²	F	Pr (> F)
Water temperature	1	73.586	0.65660	72500.6	0.001
Conductivity	1	8.831	0.07880	8700.4	0.001
Dissolved oxygen	1	26.005	0.23204	25621.2	0.001
Residual	3596	3.65	0.03257		
Total	3599	112.072	1.00000		

CHAPTER IV

DISCUSSION

The health of lakes depends on various indicators, including water temperature, conductivity, and dissolved oxygen levels. Examination of the environmental conditions of Lake Louise is essential because it exercises intense control over the lake's ecosystem. This study illustrates that Lake Louise's surface water is highly responsive to thermal alterations.

In most temperate and subtropical lakes, there is a marked annual cycle of thermal stratification, and Lake Louise is no exception. During winter, the average air temperature in the region ranges from ~ 10.8 °C in January to close ~ 12.8 °C in December and February (Climate Data, 2025). The low air temperatures and reduced sunlight (less than 7 hours per day (Climate Data, 2025) cause the temperature of the epilimnion to approach that of the hypolimnion, destabilizing the temperature and concentration gradients supporting thermal stratification. In the present study, thermal stratification started to fade away in early December 2024, with the temperature differential between the lake's epilimnion and hypolimnion decreasing to about 2 °C. In December 2017, the differential temperature was about 2 °C, while in December 2003 and 2004, it was approximately 1 °C. As a result of these changes, the lake mixes from top to bottom. In spring, average air temperatures and period of direct sunlight increase, reaching ~ 24 °C and 10.4 hours, respectively, by May. This rise is mirrored by an increase in the temperature of the surface of the lake, caused in large part by the increase in sunlight while deeper waters have no contact with the warmer air. In addition, solar warming is also restricted to the surface waters; because of the high concentrations of humic substances in Lake Louise, appreciable amounts of

solar thermal energy do not penetrate below 2.5 meter (unpublished data). As a result, thermal stratification begins, and the waters of the lake are divided into an epilimnion and a hypolimnion. Stratification continues until late fall, when air temperatures and insolation begin to drop. Isothermal conditions can occur as early as November. This basic pattern can be seen in Figures 2 – 5. The high concentrations of dissolved oxygen in the epilimnion are the result of both exchange with the atmosphere and photosynthetic activity by the members of the phytoplankton. The observed thermal stratification limits the amount of atmospheric oxygen that can enter the deep layers of Lake Louise; the rapid change in temperature across the metalimnion is associated with changes in the density of water, which, in turn, limit the diffusion of dissolved substances. These findings corroborate Noori et al. (2021) who found that the restricted diffusion of oxygen across the thermocline resulted in a dissolved oxygen deficit of 1.1 – 4.5 mg/L in the deeper layers of a warm monomictic reservoir in Iran. The organic-rich sediments that built up during the construction of the I-75 Highway from 1961 to 1963, combined with the contributions from nearby wetlands, may have played a significant role in creating the anoxic conditions seen at the lake's bottom waters (Tepper & Hyatt, 2011); consumption of these substances by heterotrophic bacteria would create an oxygen deficit environment. Aradpour et al. (2020) and Steinsberger et al. (2020) also suggest that the release of reduced substances from organic-rich sediments at the bottom of lakes plays a role in increasing sediment oxygen demand which could lower DO levels in the hypolimnion. Soluble ions from these sediments (Fukushima et al., 2017) and precipitation and seepage from nearby soils could result in greater ionic strength and higher conductivity in the deeper columns (Bischof et al., 2019; Harvey et al., 1997). The lake received inflow from rainfall in late July (before Hurricane Debby), early August (due to Hurricane Debby; 17.88 cm), late September (related to Hurricane Helene; 9.58 cm), and early November (linked to Tropical

Storm Rafael-associated storms), which featured intense winds (Debby = 25.7 m/s; Helene = 27.8 m/s) (National Weather Service, 2025a, 2025b, NOAA 2025) that mixed the epilimnion with cooler waters from below the thermocline (Figs 2 & 3). The effects of mixing during these storms, however, did not extend below 3 m, although it pushed some DO from the epilimnion down to 2.5 m – 2.6 m depths. The cooling effect of Helene's impact led to a notable drop in water temperature between late September and early October, 2024, especially in the lower epilimnion and upper thermocline. This nearly disrupted the delicate balance of stratification. In a similar situation and in the same lake, Gould et al. (2019) observed that the passage of Hurricane Irma in 2017 caused warm epilimnion waters to be mixed with cold hypolimnion waters to a depth of 3 m and a surge in DO between the 2 m to 2.5 m depths. Such storms have the potential to redistribute phytoplankton across the water column and affect the community composition, but the structure of Lake Louise seems to limit the extent of the impact to the upper 2 – 3 meters of the water column (Gould et al., 2019; Huisman et al., 2004). It should be noted that the storms impacting Lake Louise all occurred between July and the beginning of November, during the period when thermal stratification is the strongest feature of the lake. The failure to achieve complete mixing of the water column in each instance suggests that the impacts of hurricanes on the physical/chemical environment of deep stratified lakes may be limited.

Storms also impact lake systems by bringing in terrestrial substances through runoff from the surrounding lands (Woolway et al., 2020; Zwart et al., 2016); this may have contributed to the rise in conductivity observed over the course of the season near the bottom of Lake Louise (Figures 6 and 7). The disappearance of the thermal gradient in winter can enhance a lake's quality by allowing dissolved substances such as oxygen to reach its deeper waters, it can as well

move dissolved substances indicated by the higher conductivity to the surface water; some of these substances may lead to a deterioration of the surface water quality and contribute to observed changes in the phytoplankton community (Kim et al., 2024; Noori et al., 2021). The increasing trends in the lake's water temperature and conductivity but a decreasing trend in oxygen content shows crucial changes in the ecosystem's water quality over time. The declining DO content could be due to warming of the lake's water temperature, particularly in the summer, as warm waters are not able to hold much oxygen (Limburg et al., 2020). However, warmer temperatures could also favor the development of a new phytoplankton association.

The impacts of major storms on the phytoplankton of a lake may be harder to predict. After the passage of Hurricane Irma in 2017, the numbers of cyanobacteria in the phytoplankton increased significantly (Gould et al., 2019), whereas in 2024, phytoplankton numbers decreased. This suggests that the overall impact of a storm on the phytoplankton of a lake may be influenced by the lake's physical and chemical states before and after the storm. The increased numbers of phytoplankton after Hurricane Irma may have resulted from nutrient upwelling and increased mixing in the water column during the storm. Additionally, the increased numbers of phytoplankton corresponded to the increased chlorophyll *a* pattern in the epilimnion of the lake before and after the passage of Hurricane Irma (see Figure 15). Brief events like storms can disturb normal balance between organisms in the food web and result in temporary situations where phytoplankton may exceptionally grow and multiply. This quick growth can result in an increase in the uneven distribution of phytoplankton (Chen et al., 2020). Although the surface temperature did decrease slightly during Irma, which can slow phytoplankton growth (Trombetta et al., 2019), changes in the depth-distribution of oxygen and nutrients, can lead to phytoplankton growth and a depth-dependent distribution (see Kasprzak et al., 2017; Mesman et al., 2022;

Whitt et al., 2019). The contrasting decline in phytoplankton assemblage, particularly the cyanobacterial assemblage, in the 2024 monitoring period, suggests that for Debby and Helene the flushing effect of the storms on the surface layers of Lake Louise due to increased rainfall and high flow rate may have been the most impact. This event mirrored the patterns of chlorophyll *a* in the lake, revealing the low concentrations throughout the water column in early August and late September (see Figure 14). The intense rainfall that hit the lake could have swept away vital nutrients (Stockwell et al., 2020), which are essential for nourishing the growth of these species. In addition, the dominant cyanobacteria in Lake Louise, *Dolichospermum* spp., *Aphanizomenon* spp., and *Microcystis* spp., produces gas vesicles, which may have trapped them in the upper levels of the lake when flushing occurred. These effects would have been exacerbated by the timing of the passage of Helene, a month later in the season than Irma, and by the heavy rainfall accompanying Hurricane Rafael about 6 weeks later.

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APPENDIX A:
Charts and Figures



Figure 1: Top left. A view of Lake Louise showing the surrounding vegetation. Bottom left. Satellite image of Lake Louise, Georgia from Google Earth © 2024.

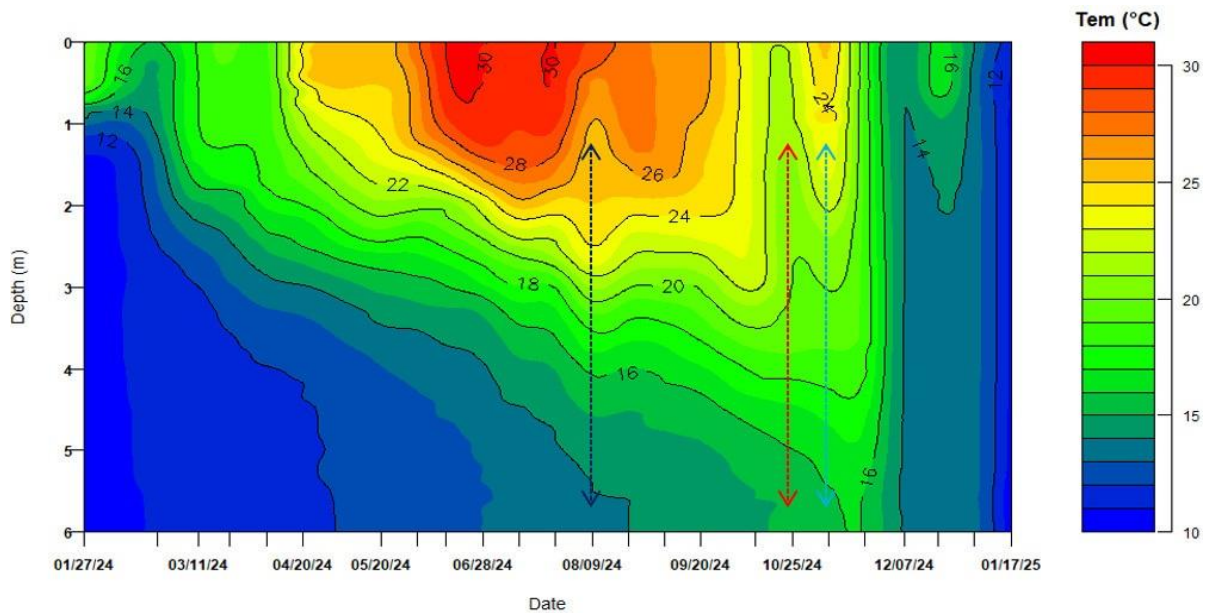


Figure 2: Variation in temperature from January 27, 2024, to January 17, 2025. The impact of Hurricane Debby is highlighted by dark blue dashed arrow; Hurricane Helene's effect is shown in red dashed arrow; influence from Storm Rafael is represented by light blue dashed arrow.

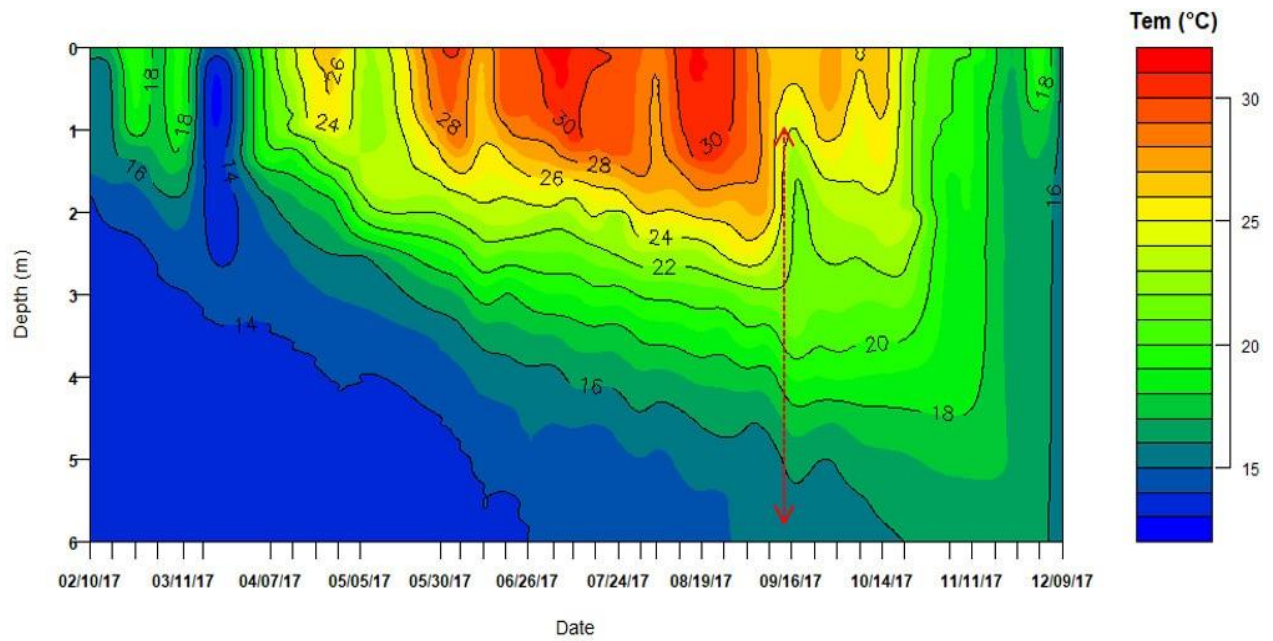


Figure 3: Variation in temperature from February 10, 2017, to December 9, 2017. Hurricane Irma's effect is shown in red dashed arrow.

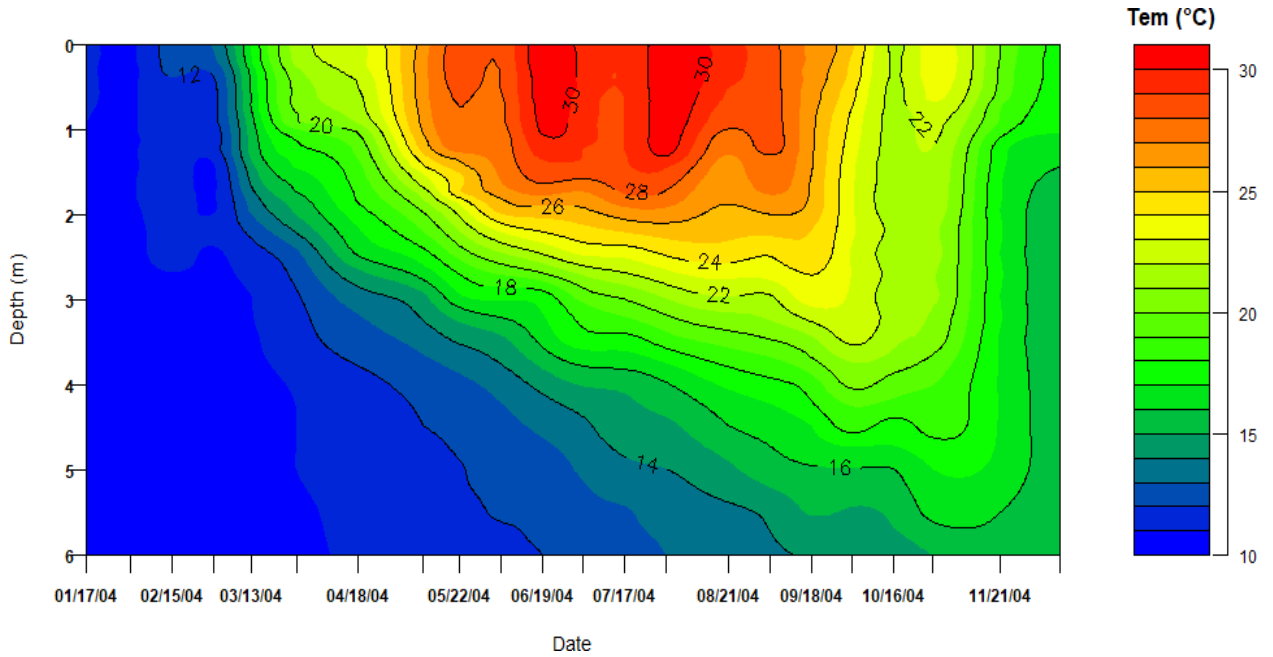


Figure 4: Variation in temperature from January 17, 2004 to December 11, 2004.

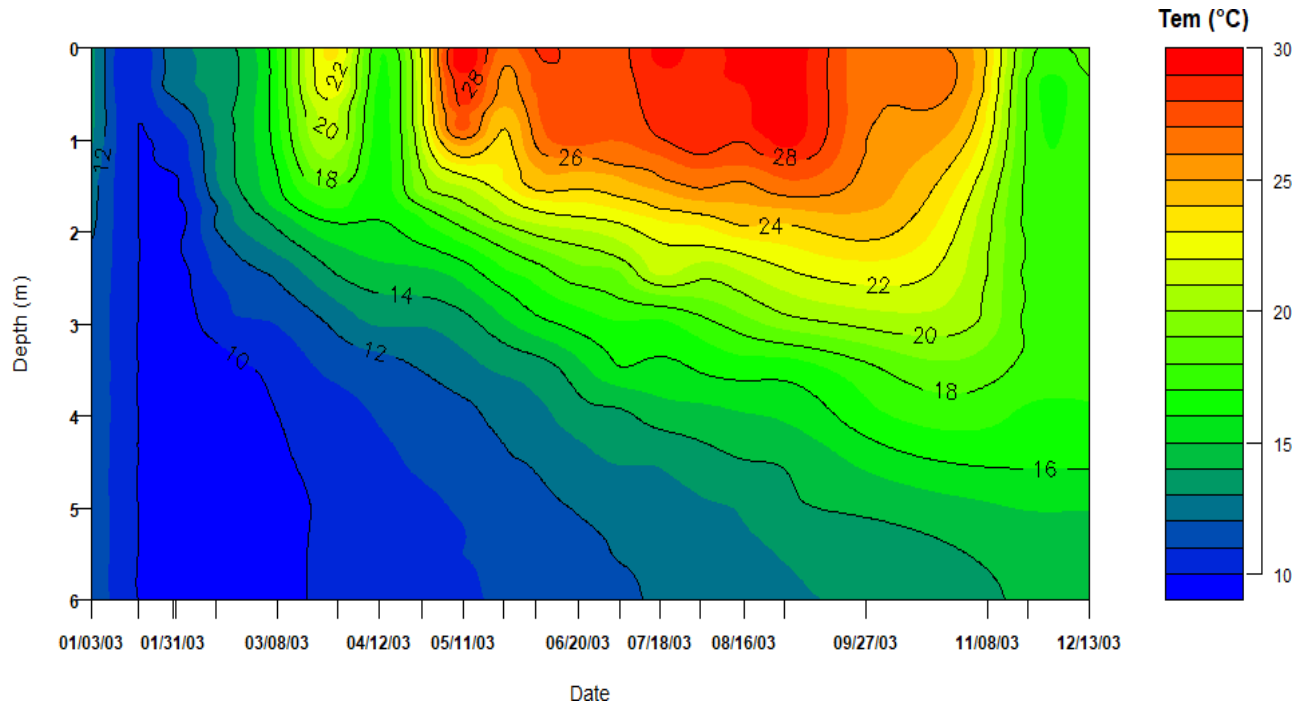


Figure 5: Variation in temperature from January 3, 2003, to December 13, 2003.

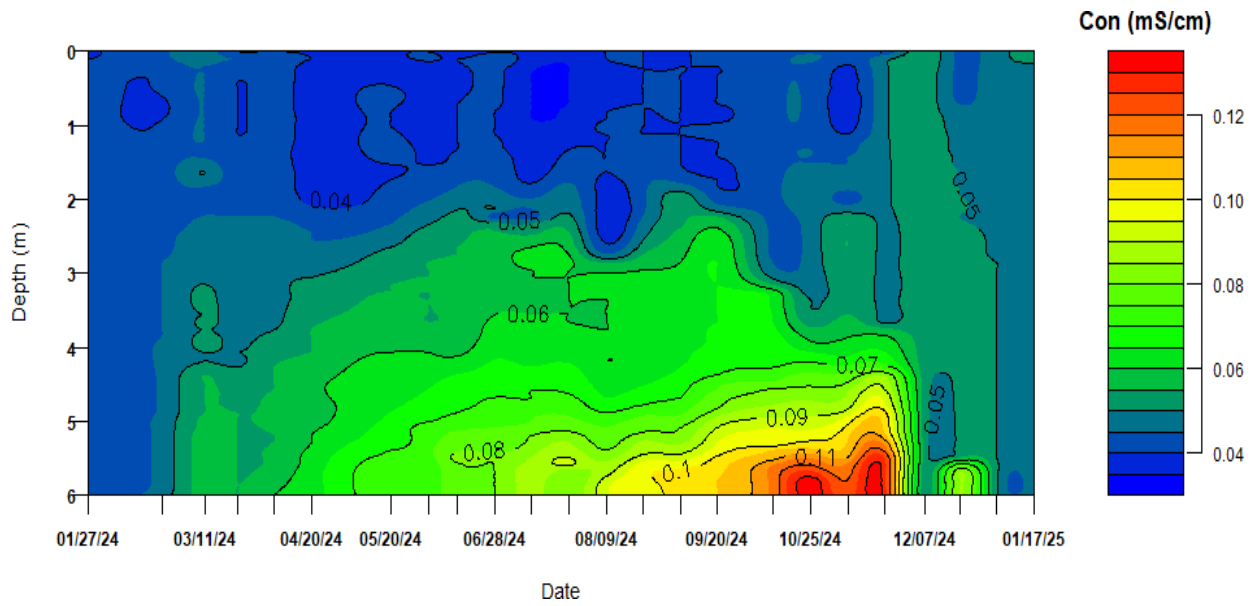


Figure 6: Variation in conductivity from January 27, 2024 to January 17, 2025.

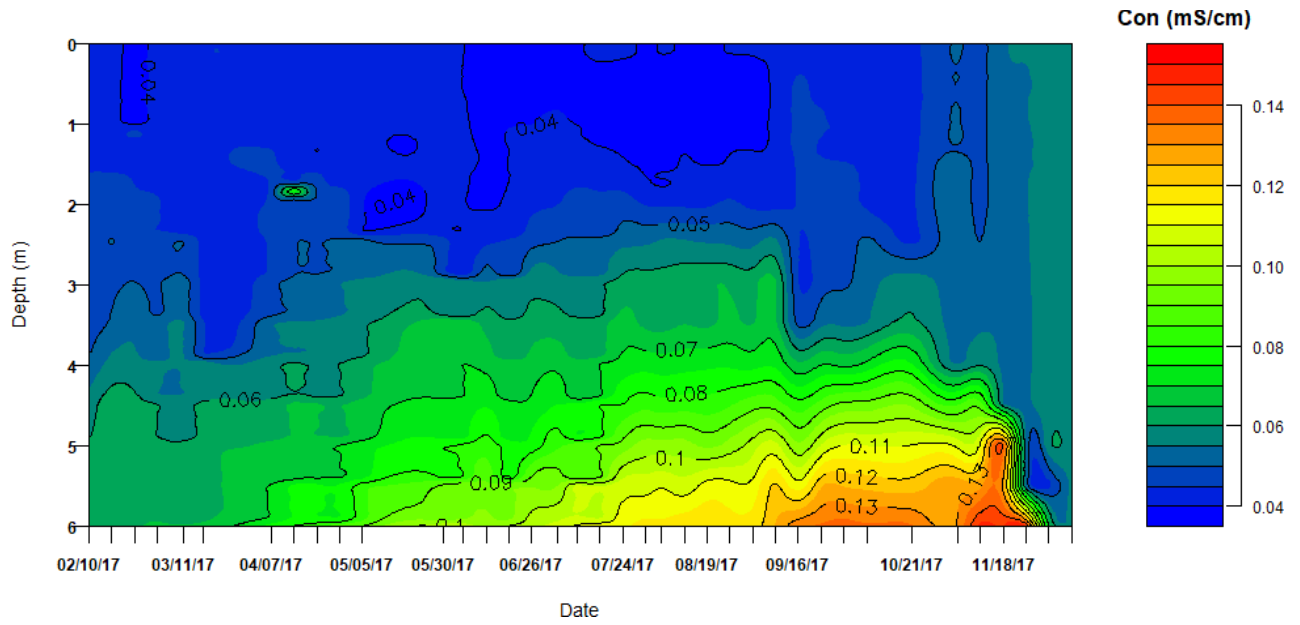


Figure 7: Variation in conductivity from February 10, 2017 to December 09, 2017.

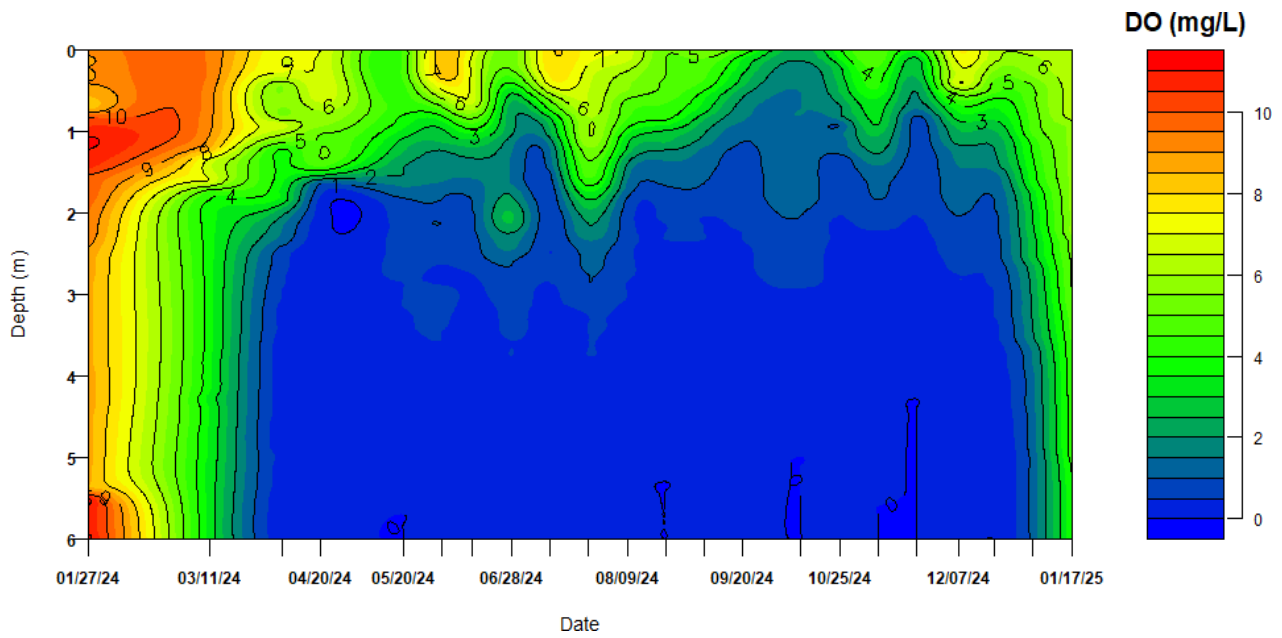


Figure 8: Variation in Oxygen from January 27, 2024 to January 17, 2025.

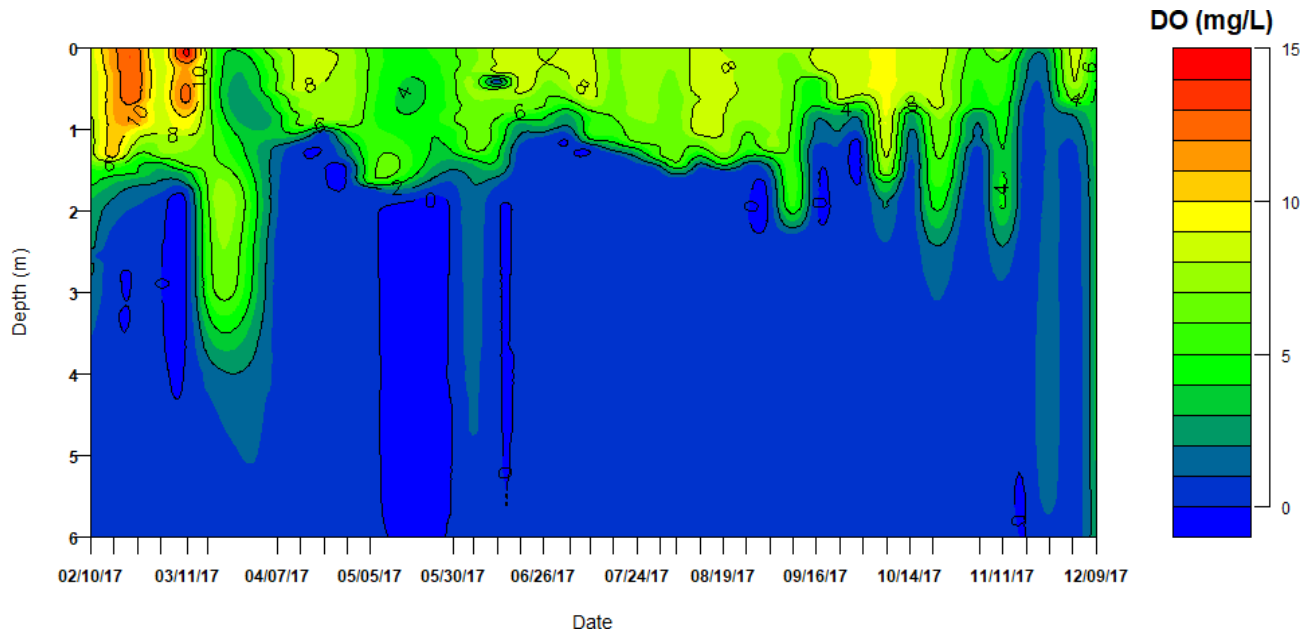


Figure 9: Variation in Oxygen from February 10, 2017, to December 09, 2017.

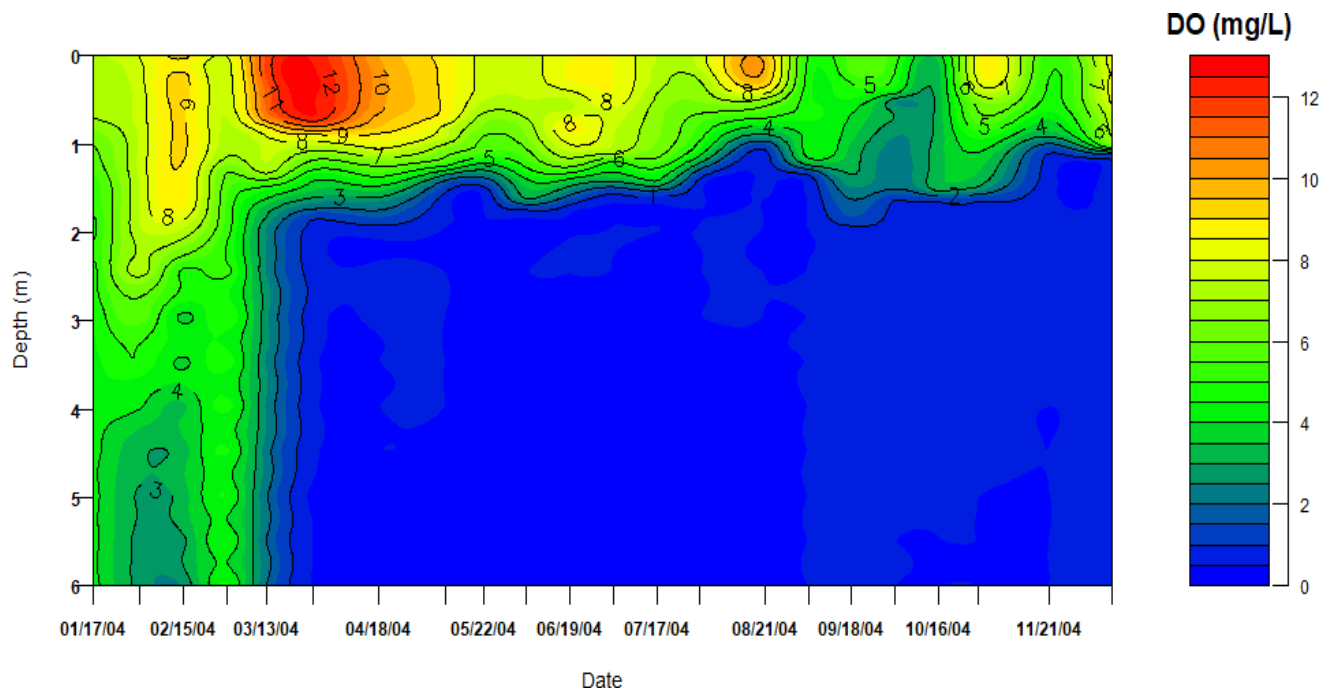


Figure 10: Variation in oxygen from January 17, 2004 to December 11, 2004.

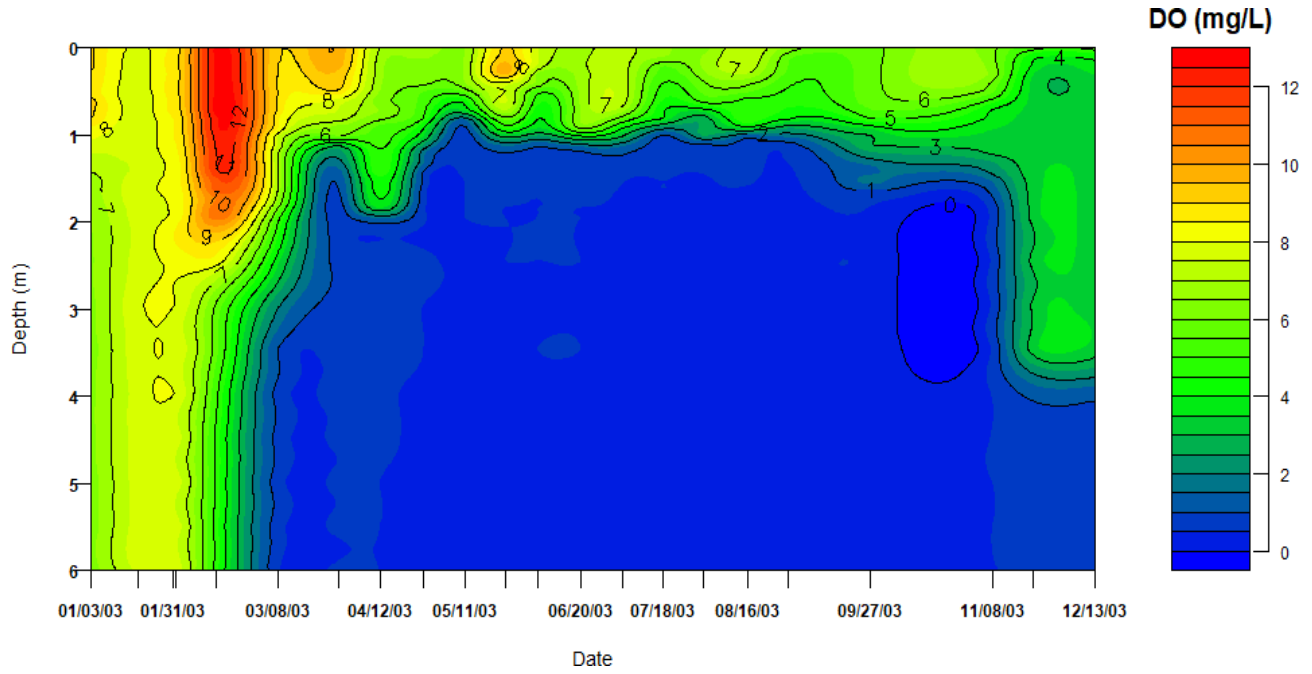


Figure 11: Variation in oxygen from January 3, 2003, to December 13, 2003.

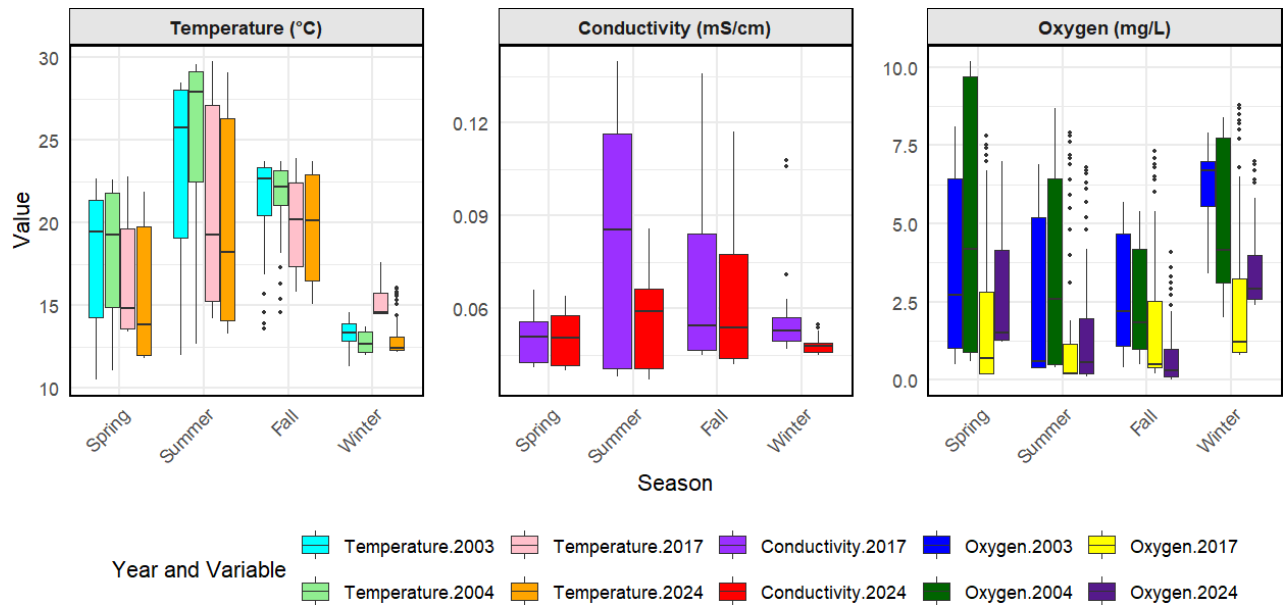


Figure 12: Boxplot showing seasonal differences in temperature, conductivity and oxygen.

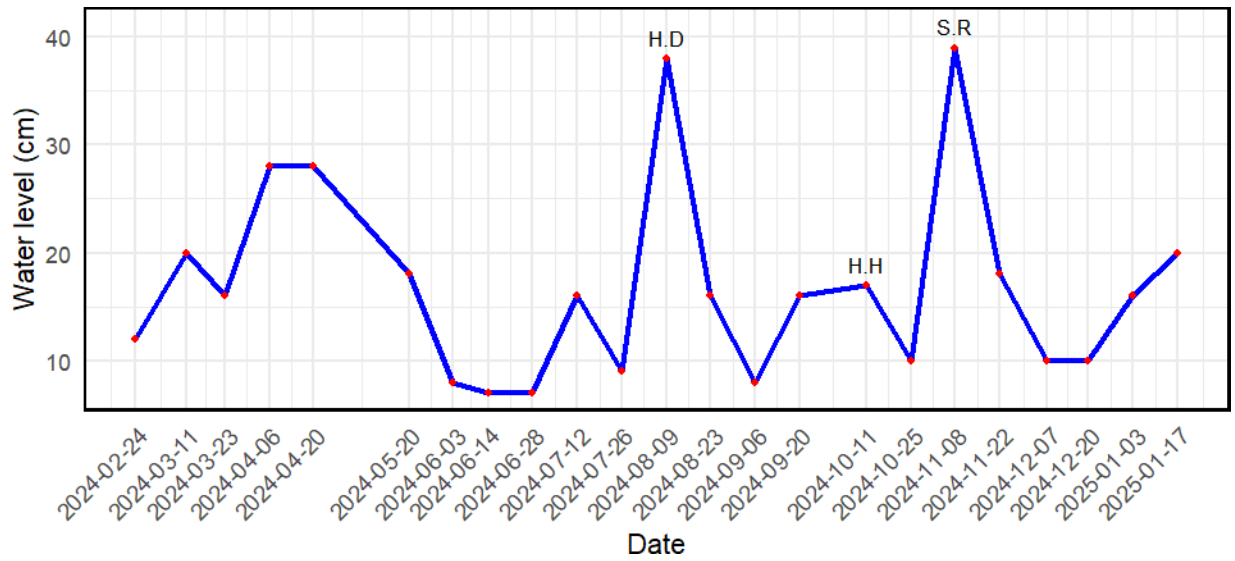


Figure 13: Lake Louise's water level from February 24, 2024 to January 17, 2025: H.D (Hurricane Debby), H.H (Hurricane Helene) and S.R (Storm Rafael).

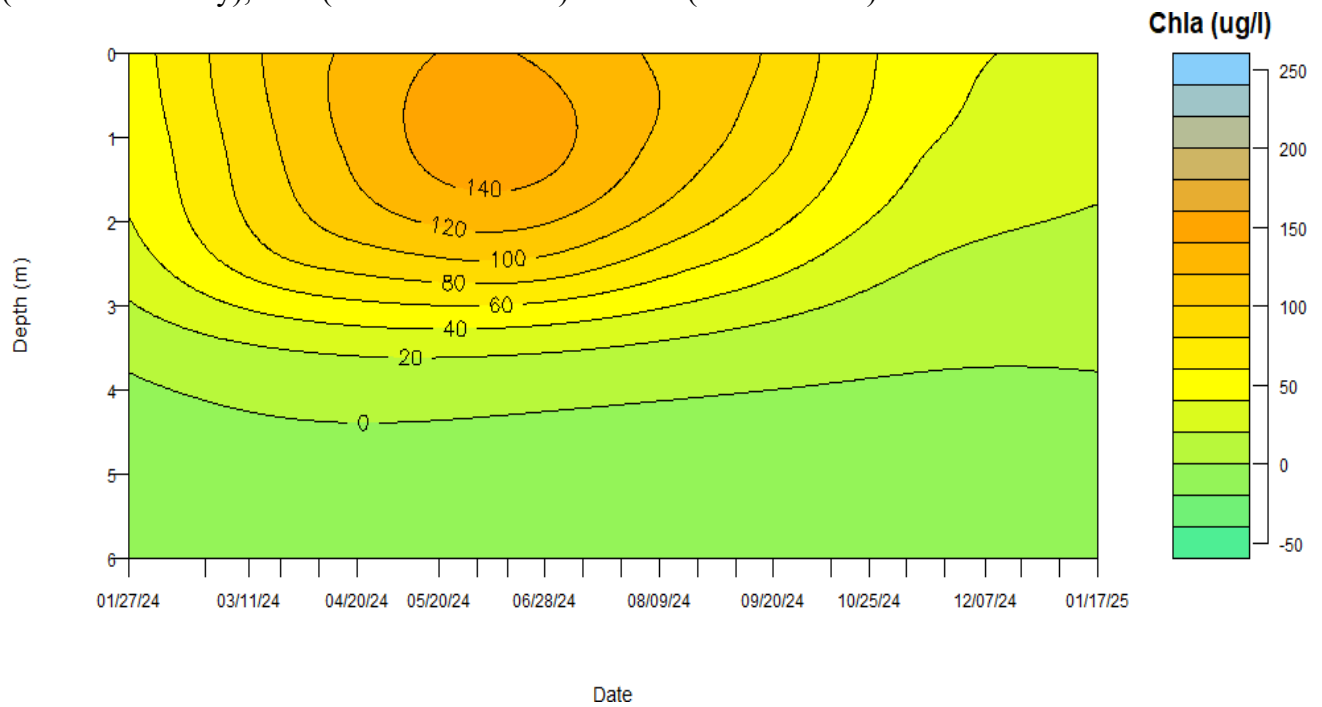


Figure 14: Chlorophyll *a* pigment ($\mu\text{g} \cdot \text{L}^{-1}$) in samples collected from 0 – 5 meters in Lake Louise from January 27, 2024 – January 17, 2025. High concentrations observed in the epilimnion majorly during thermal stratification period.

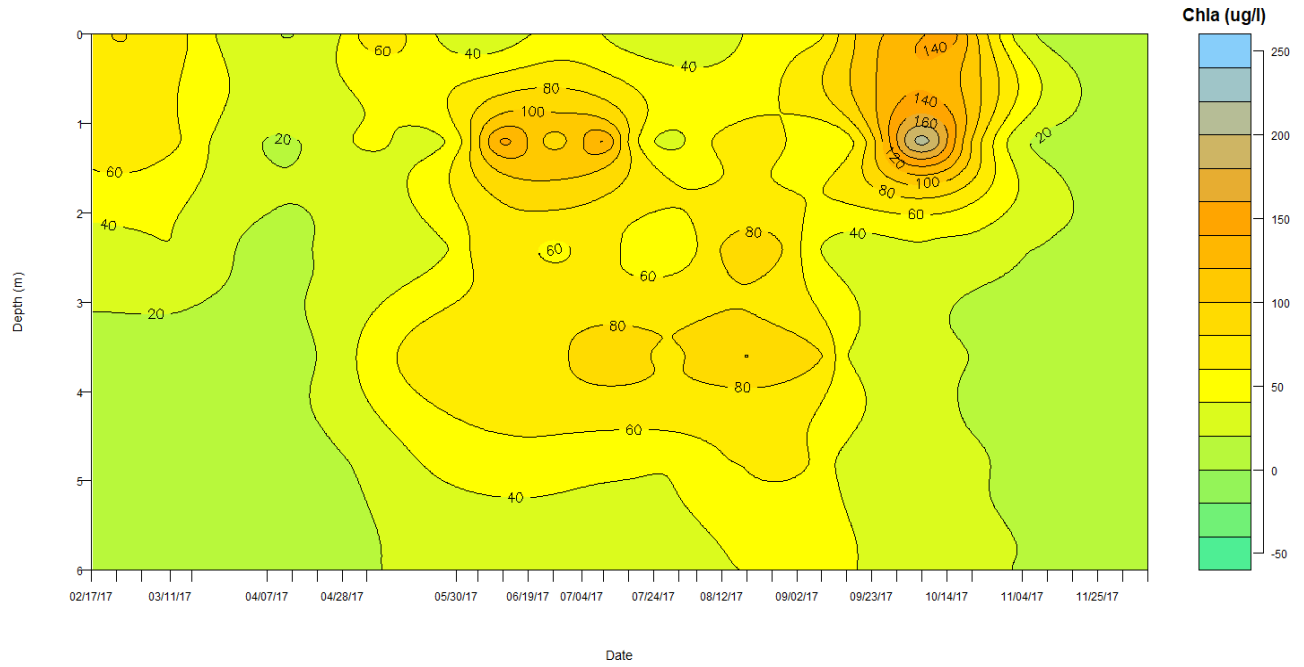


Figure 15: Chlorophyll *a* pigment ($\mu\text{g} \cdot \text{L}^{-1}$) in samples collected from 0 – 5 meters in Lake Louise from February 17, 2017 – December 9, 2017. High concentrations observed in the epilimnion, and chlorophyll presence throughout the vertically mixed water column.



Figure 16: Chlorophyll *a* pigment ($\mu\text{g} \cdot \text{L}^{-1}$) in samples collected from 0 – 5 meters in Lake Louise from January 17, 2004 – December 11, 2004. High concentrations observed in the epilimnion, and chlorophyll presence throughout the vertically mixed water column from Middle of May to Mid-October, 2004.

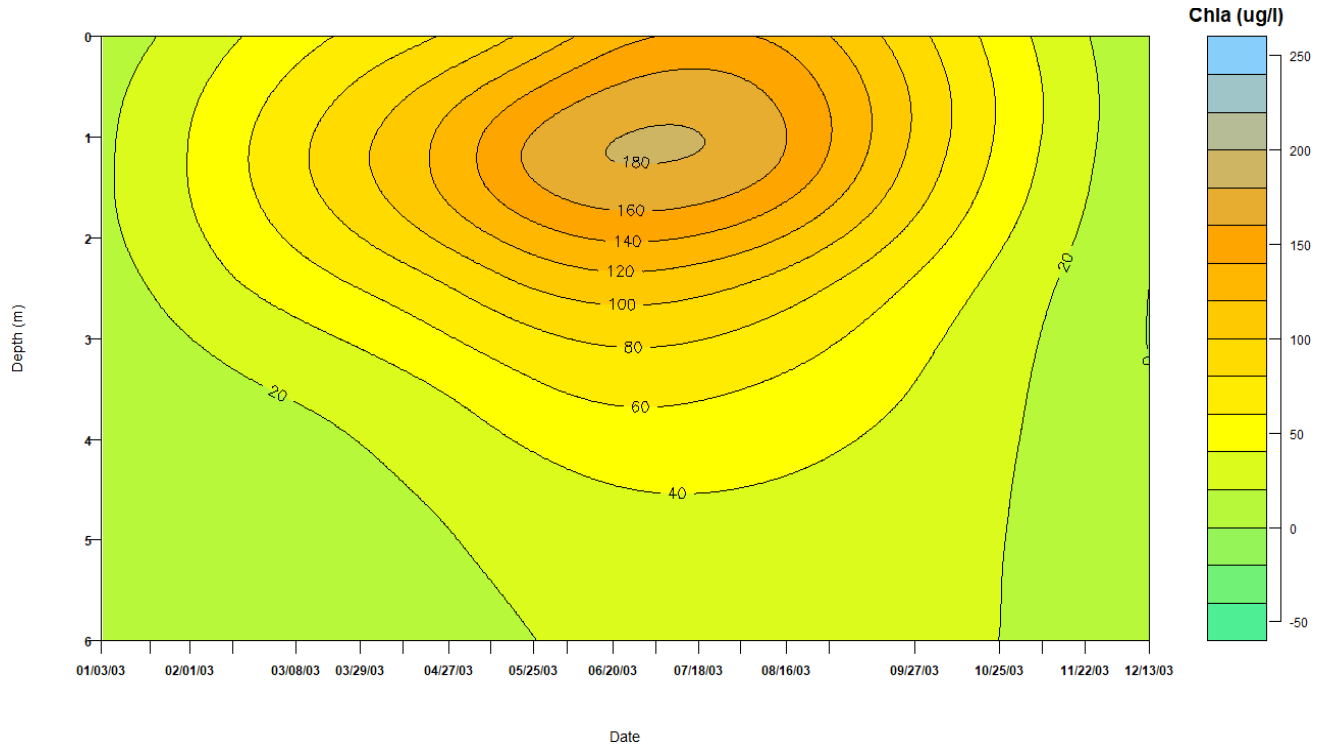


Figure 17: Chlorophyll *a* pigment ($\mu\text{g} \cdot \text{L}^{-1}$) in samples collected from 0 – 5 meters in Lake Louise from January 3, 2003 – December 13, 2003. High concentrations observed in the epilimnion, and decreasing with depth.

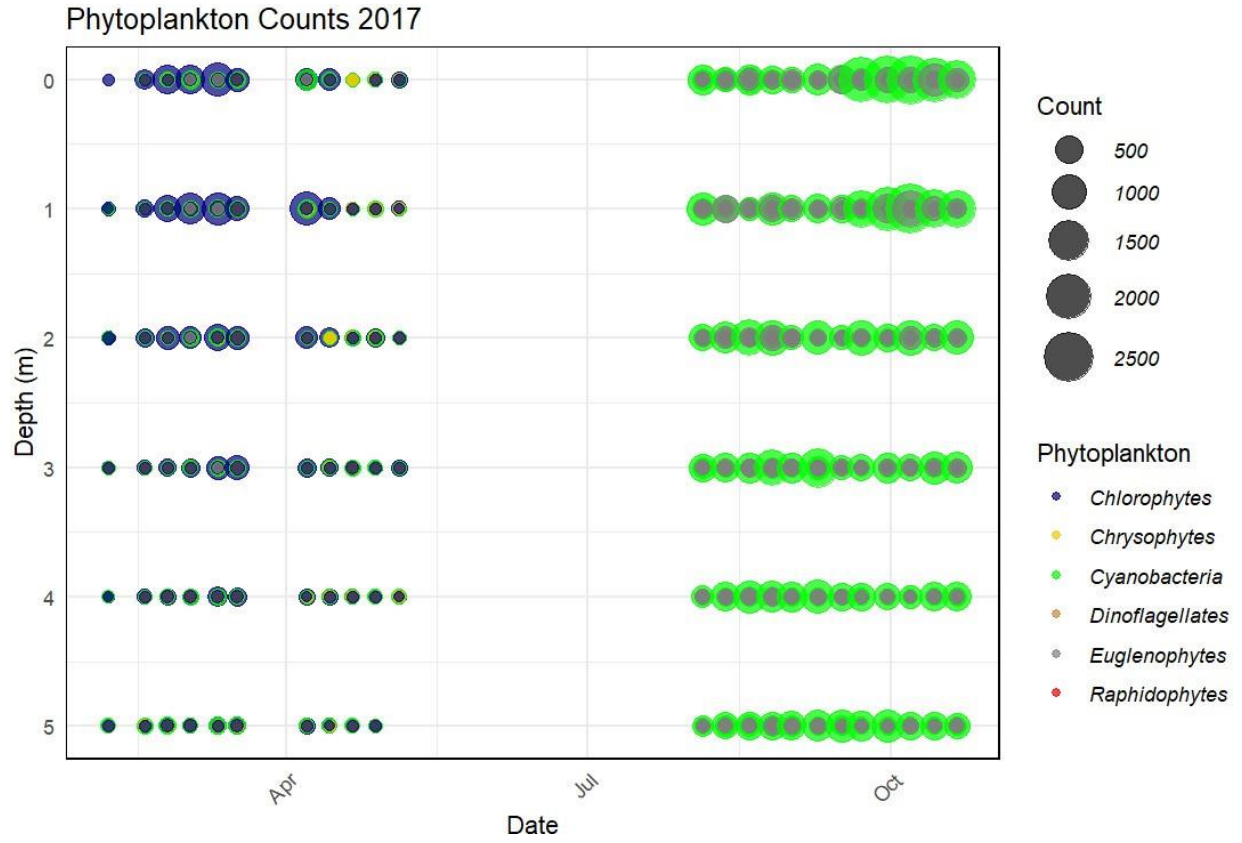


Figure 18: Phytoplankton counts in Lake Louise from February 6 to October 21, 2017.

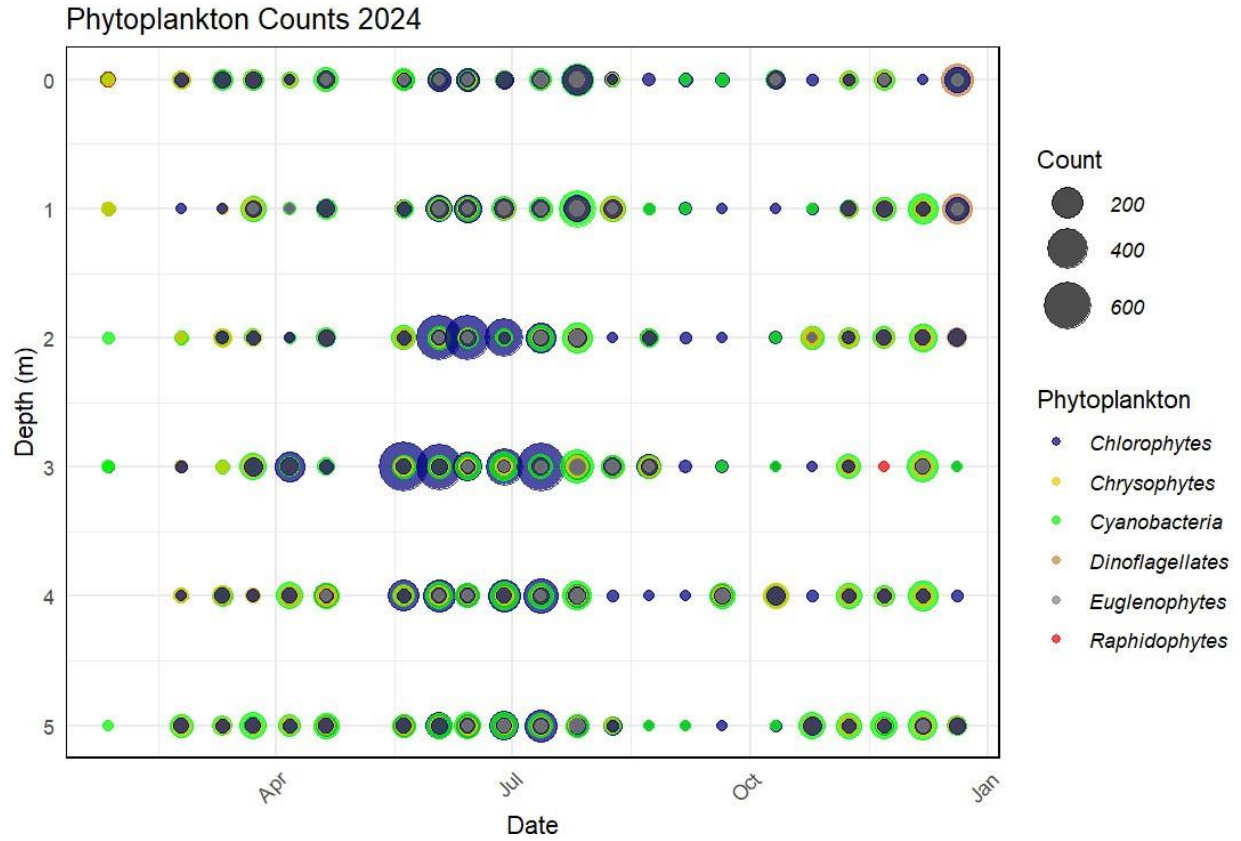


Figure 19: Phytoplankton count in Lake Louise from January 27 to December 20, 2024.

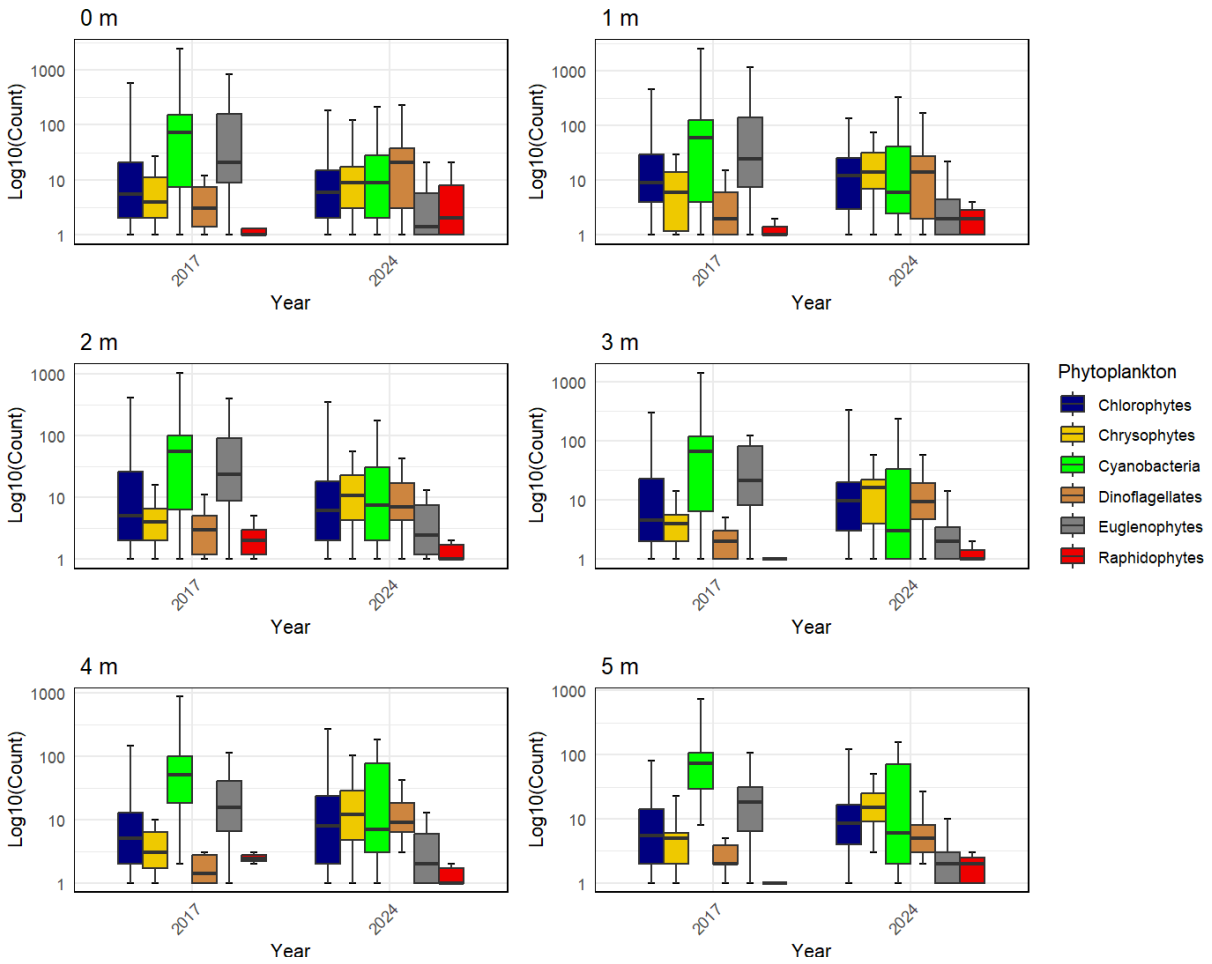
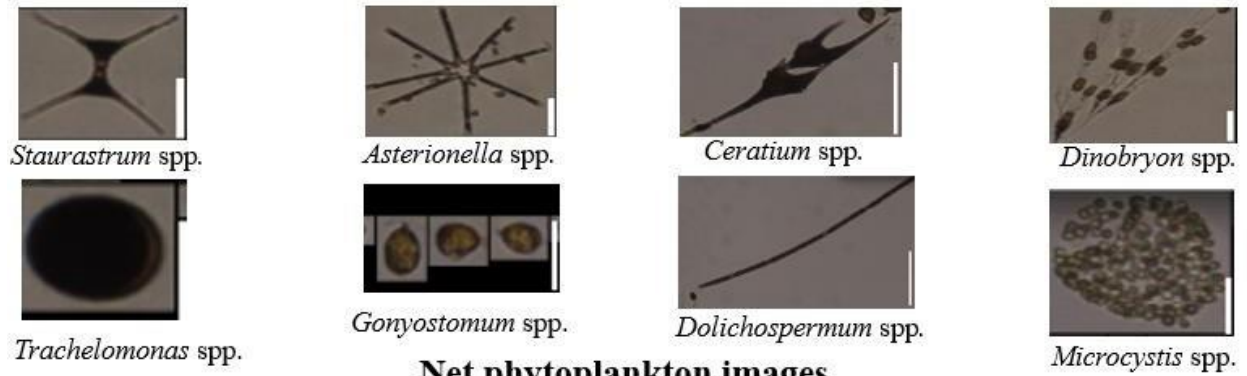


Figure 20: Boxplot showing variations in phytoplankton groups in Lake Louise in 2017 and 2024.

FlowCAM images



Net phytoplankton images

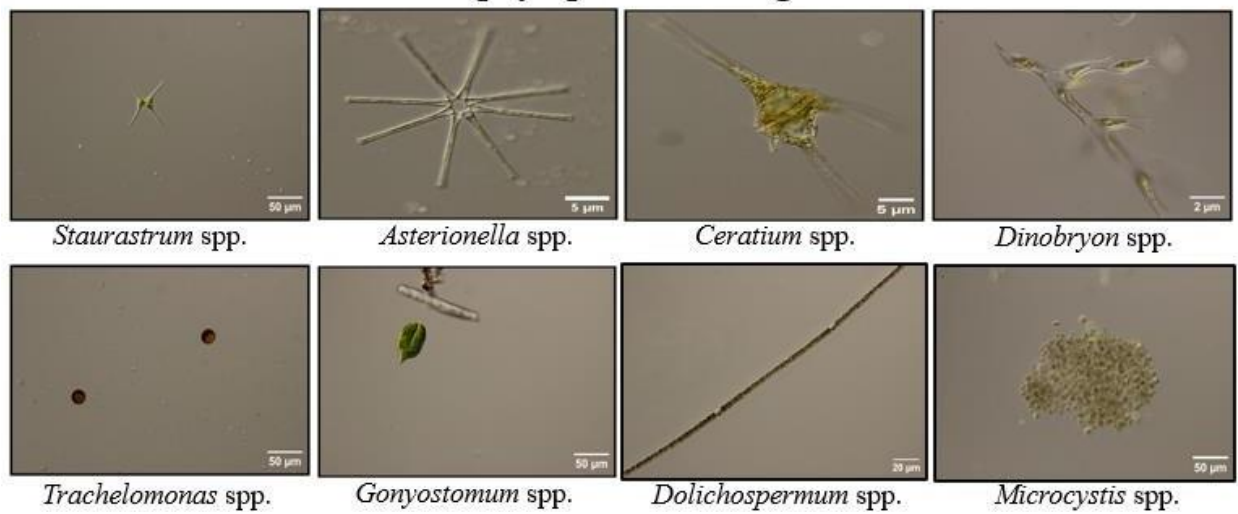


Figure 21: Comparison of FlowCAM images to light micrographs of living net phytoplankton samples. FlowCam images: *Staurastrum* spp. (50 μm), *Asterionella* spp. (5 μm), *Ceratium* spp. (5 μm), *Dinobryon* spp. (2 μm), *Trachelomonas* spp. (50 μm), *Gonyostomum* spp. (50 μm), *Dolichospermum* spp. (20 μm) and *Microcystis* spp. (50 μm).