Restoration of Lajoie Lake: Investigating Climatically Induced Meromixis

by

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Abstract

Lajoie Lake is a small montane lake located 90 km northwest of Lillooet, British Columbia. In recent decades, long-time residents have observed water quality degradation and eutrophication despite no apparent increase in external nutrient inputs. This study investigates an alternative hypothesis for the cause of this degradation: Lajoie Lake's topographic shielding predisposed it to a climatically induced mixing regime shift. Based on lake thermal and chemical properties collected during the 2022 ice-off season, Lajoie Lake is now meromictic and does not undergo complete spring and autumn circulation. The lack of sufficient wind energy during autumn suggests that topographic shielding predisposed Lajoie Lake to this shift, but climate change likely facilitated the transition. The mixing regime change likely resulted in nutrient regeneration, which contributes to increased primary productivity and the water quality changes observed. Lake circulation using compressed air to induce complete mixing is recommended to recover dimictic lake processes.

Keywords: Meromixis; Stratification; Climate Change; Water Quality; Restoration; Lake Aeration

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List of Acronyms

DO	Dissolved oxygen
P	Phosphorus
TDS	Total dissolved solids
SSI	Schmidt Stability Index
W	Wedderburn number
PSB	Purple sulphur bacteria
RCP	Representative concentration pathway
SCFM	Standard cubic feet per minute

Glossary

Anaerobia	A complete lack of oxygen, free-floating and chemically bound.
Anoxia	A lack of free-floating oxygen, but chemically bound oxygen remains.
Chemocline	The middle stratification layer of a meromictic lake. Characterised by a rapid increase in density with depth, often influenced by the water's chemical content.
Crenogenic	A meromixis formation mechanism whereby salt rich groundwater contributes to a strong chemocline that restricts whole-lake mixing.
Dimixis	A lake circulation regime characterised by two mixing periods per year.
Ectogenic	A meromixis formation mechanism whereby salt rich surface water contributes to a strong chemocline that restricts whole-lake mixing.
Endogenic	A meromixis formation mechanism whereby abundant organic decomposition leads to salt accumulation that contributes to a strong chemocline that restricts whole-lake mixing.
Epilimnion	The topmost layer of a holomictic lake during summer stratification. Characterised by its warm, mixed, and well oxygenated water.
Eutrophic	A state of high lake productivity with abundant nutrients and low water clarity.
Holomictic	Lake circulation that is complete throughout the water column. Opposite of meromictic.
Hypolimnion	The bottommost layer of a holomictic lake during summer stratification. Characterised by its cold and quiescent water that can become oxygen depleted.
Hypoxia	A low concentration of oxygen, often defined as below 2 mg/L.
Internal Seiches/Waves	A natural phenomenon caused by sustained winds and characterized by oscillations of the water layers at the pycnocline.
Katabatic Wind	Wind commonly generated in glacially headed valleys in which upslope air cools faster than downslope air and the subsequent density difference creates outflow wind.
Limnology	The study of lakes.
Littoral Zone	The shallow zone of a lake along its shoreline, generally defined as regions less than 6 meters deep.

Meromixis	A lake circulation regime characterised by a complete lack of circulation and permanent density stratification. Opposite of holomixis.
Mixolimnion	The topmost layer of a meromictic lake. Characterised by its mixed and well oxygenated water that is usually chemically distinct from the monimolimnion.
Monimolimnion	The bottommost layer of a meromictic lake. Often characterised by its quiescent, oxygen depleted and chemically rich water.
Monomictic	A lake circulation regime characterised by a single mixing period per year.
Morphogenic	A meromixis formation mechanism whereby the shape of the lake basin and its surrounding topography limit the wind energy the lake receives such that it does not have sufficient energy to circulate the entire water column.
Oligotrophic	A state of low lake productivity with limited nutrients and high water clarity.
Polymictic	A lake circulation regime characterised by more than two mixing periods per year.
Pycnocline	The middle layer of a stratified lake. Characterised by a rapid increase in density with depth due to any parameter than influences density. The thermocline and chemocline are types of pycnoclines.
Relative Depth	The ratio between a lake's maximum depth and its surface area. A high relative depth can restrict whole-lake circulation and lead to morphogenic meromixis.
Schmidt Stability Index	A derived limnological parameter that quantifies the amount of energy required per unit area of lake surface to completely mix the water column with no heat gain or loss.
Specific Conductance	A water sample's ability to conduct an electric current standardised to 25 °C. Acts as a proxy for the concentration of dissolved solids.
Stratification	A phenomenon in lakes where density differences divide the lake into distinct layers that do not mix throughout the duration of stratification.
Thermocline	The middle layer of a holomictic lake during summer stratification. Characterised by its rapidly declining temperature with depth that creates a density gradient in the water column.
Topographic Shielding	When the surrounding topography of a lake shelters it from the prevailing winds. A high degree of shielding can restrict whole-lake circulation and lead to morphogenic meromixis.

Wedderburn Number	A derived limnological parameter calculated as the ratio between the forces acting to mix the water column and the forces acting to stabilise the water column. Lower values indicate a greater chance of mixing.

Executive Summary

Lajoie Lake is part of the Bridge River watershed in southwest British Columbia, 90 km northwest from Lillooet. Lajoie Lake is small, occupying 41 ha with a mean depth of 12 m and maximum depth of 23 m. Historically, the lake was oligotrophic with pristine water quality. However, despite no apparent increase in external nutrient inputs into Lajoie Lake, long-time residents have observed decreasing water quality in recent decades. I hypothesized that Lajoie Lake's topographic shielding predisposed it to a climatically induced mixing regime shift, ultimately resulting in the observed degradation.

I observationally tested this hypothesis by answering two questions during the 2022 ice-off season. What is the stratification and annual circulation regime of Lajoie Lake and how does it influence hypolimnetic oxygen concentration? Does the shape of the lake basin topographically shield the water surface from wind and contribute to the lack of circulation? I answered these questions observationally with continuous sampling of the water column's temperature and the local wind speed and direction. Additionally, I collected vertical profiles of the water column's dissolved oxygen concentration and electrical conductivity biweekly to monthly from May to November 2022.

Lajoie Lake exhibited thermal stratification rapidly after ice-off in April and did not fully mix before freeze-over in late November. Furthermore, the bottom water layer remained anaerobic throughout the observation period. Wind patterns were greatly influenced by month; 'windy' conditions were most common in July and wind was rare in November. All evidence supports the hypothesis that Lajoie Lake does not fully circulate. Results from the weather station demonstrate a dearth of wind energy during the critical fall mixing period, supporting the hypothesis that topographic shielding predisposed Lajoie Lake to this change. Overall, this study supports the hypothesis that water quality decline in Lajoie Lake is caused by climatically induced meromixis resulting in internal nutrient regeneration and increased primary productivity.

From these results I outline recommendations to restore ecosystem processes and water quality using artificial circulation, mimicking the historical dimictic mixing periods in the spring and autumn. This project adds critical information to a body of literature demonstrating the far-reaching impacts of climate change on lakes globally and provides a restoration model for lakes similarly impacted as Lajoie.

1. Introduction

1.1. Lake stratification and mixing regime

Density stratification is a natural phenomenon exhibited in lakes globally. Stratification primarily forms via solar heating of the lake creating density differences in the water column (Boehrer & Schultze 2008). Three distinct layers form: the warm, mixed epilimnion at the surface, the thermocline, and the cold, quiescent hypolimnion at the bottom. The density gradient across the thermocline restricts the circulation of water and movement of dissolved substances between the epilimnion and the hypolimnion (Boehrer & Schultze 2008). Therefore, the hypolimnion behaves like a closed system and does not receive atmospheric oxygen inputs for the duration of stratification and hypolimnetic dissolved oxygen (DO) is only replenished during mixing events that predictably occur based on a lakes circulation regime.

Multiple factors determine a lake's circulation regime, including morphometry, elevation, latitude, and climate (Boehrer & Schultze 2008). The most common stratification regime in temperate climates is holomictic dimixis: a lake with two periods of complete mixing per year (Boehrer & Schultze 2008). Dimictic lakes freeze in the winter, stratify in the summer, and circulate completely during the spring and autumn when the lake lacks a density gradient to resist mixing via wind energy – the predominate force that induces mixing (Kirillin et al. 2012). These periods of circulation allow for the penetration of DO into the depths of the lake. Density gradients in the summer are too strong for wind energy to overcome and stratification persists until the water temperature decreases in the fall (Boehrer & Schultze 2008). Inverse stratification occurs under ice cover as water is densest at about 4°C and immediate under-ice water temperature is about 1°C (Kirillin et al. 2012).

Ice cover and stratification of lakes can result in the hypolimnion becoming hypoxic (< 2 mg/L DO (Diaz 2001)), anoxic, or anaerobic. Respiration of organic matter and chemical reactions both exert considerable oxygen demand within the hypolimnion and the lake sediment (Beutel 2003; Ellis & Stefan 1989). If stratification persists for long enough, the oxygen demand can overcome the supply provided during mixing and the hypolimnion becomes oxygen depleted (Ellis & Stefan 1989; Jane et al. 2021). Hypolimnetic oxygen depletion has consequences for lake water quality (described in section 1.4) and for lake biota (Orihe et al. 2017; North et al. 2014). Unfortunately, hypoxic conditions are becoming more prevalent worldwide as one of the ongoing impacts of climate change on lakes globally (Jenny et al. 2016; Jane et al. 2021).

1.2. Climate change and lakes

Global climate is rapidly changing, and Canada is projected to warm at a higher rate relative to the planetary average (Bush & Lemmen 2019). Small lakes are especially susceptible to warming temperatures as they respond directly and rapidly to climatic shifts (Adrian et al. 2009). Consequences of warming include eutrophication (Spears et al. 2011), changes in plankton communities, and the decline of fish populations (North et al. 2014). Lakes often react uniquely to changing conditions based on their individual physical and biological characteristics (Adrian et al. 2009). Therefore, it is vital to investigate each in their own context to determine how they may be impacted by climate change.

One immediate impact of climate change on temperate lakes is warming surface waters, which have generally increased since the 1980s (Jane et al. 2021). Warming surface water can lead to algae blooms and high surface DO, but higher temperature also promotes the increase of harmful cyanobacteria (Kosten et al. 2012). Increased surface water temperature may also decrease the habitat available to temperate aquatic fish species, such as rainbow trout (*Oncorhynchus mykiss*), that cannot tolerate acute exposure above 24° C (Black 1953).

Additionally, climate change is anticipated to significantly alter circulation regimes of lakes globally (Woolway & Merchant 2019). Warming temperatures have already increased both the strength and duration of summer stratification in lakes worldwide (Woolway & Merchant 2019; Jane et al. 2021). Extended stratification is anticipated to eventually result in complete mixing regime shifts in lakes within several decades (Kirillin 2010; Woolway & Merchant 2019). Dimictic lakes are predicted to first become polymictic (more than two mixing events per year), then monomictic (one mixing event per year) (Woolway & Merchant 2019). Altered mixing regimes and prolonged stratification leads to more frequent and longer hypoxia events in the hypolimnion (Jane et al. 2021). As described in section 1.4, low hypolimnetic DO results in increased nutrient availability and lower water quality (Orihe et al. 2017; North et al. 2014).

Changes to a lake's circulation regime can impact lake biota and trophic structure. Increased nutrient levels from internal loading can not only change the abundance of phytoplankton, but also its species composition and relative abundance (Sommer 1985; North et al. 2014). This has cascading effects up the lake food web, altering native fish communities, and lowering their abundance (Ficke et al. 2007). Additionally, many fish species have strict DO and thermal tolerances (Black 1953; Davis 1975). High surface temperatures and low hypolimnetic DO from strengthened stratification causes a temperature-oxygen squeeze, reducing fish habitat to a narrow band of the water column (Kerker 2020).

1.3. Meromixis

Climatically induced shifts in lake mixing regimes are widely expected to occur in dimictic lakes, but a transition to meromictic regimes is not currently anticipated as a result of climate change. Unlike other mixing regimes discussed, a meromictic lake never destratifies and mixes (Boehrer & Schultze 2008). Meromictic lakes are rare (Hall & Northcote 2012) and their unique properties from permanent stratification resulted in the development of specific terminology to differentiate them from holomictic lakes (Hutchinson 1957). The bottom layer that never circulates with upper layers is the monimolimnion and the top layer is the mixolimnion. The density gradient between the two layers is usually referred to as the chemocline, highlighting the chemical properties that create the density differences, but is also known as the pycnocline. Interestingly, the mixolimnion often acts like a mixing lake and thermally stratifies into an epilimnion, thermocline, and hypolimnion (Boehrer et al. 2017).

In contrast to the thermal stratification of dimixis, chemical properties and high concentrations of dissolved salts control the density gradient in meromictic lakes. (Boehrer & Schultze 2008; Boehrer et al. 2017). Chemical stratification develops several different ways and multiple attempts have been made to classify them (Hutchinson 1957; Walker & Likens 1975; Hakala 2004). The consensus defines four modes of meromictic formation: crenogenic, ectogenic, endogenic, and morphogenic. Most meromictic lakes are formed by external salt inputs (Hakala 2004), either from mineralized groundwater (crenogenic) or surface water (ectogenic) inflows (Walker & Likens 1975). Conversely, endogenic meromixis (also known as biogenic meromixis) arises internally from the accumulation of salts as organic matter decomposes (Walker & Likens 1975).

Morphogenic formation is the least common route to meromixis (Hakala 2004). Rather than developing a strong chemocline that resists mixing, the morphometric properties of these lakes restrict the amount of wind energy to less than is required to induce circulation (Halsey 1968; Walker & Likens 1975). Morphogenic meromixis results from topographic shielding (Halsey 1968), a high relative depth (McNaughton & Lee 2010), or from a combination of both (Hakala et al. 2004). Topographic shielding occurs when the surrounding terrain physically blocks the prevailing winds from acting upon the lake. A lake's relative depth (Z_r) is the ratio (as a percent) between its maximum depth (Z_m) and its surface area (A_0) as a circle. It is calculated as:

$$Z_r\,(\%) = 50 Z_m \sqrt{\frac{\pi}{A_0}} \qquad (1)$$

A high relative depth restricts mixing as it indicates low fetch relative to the depth of water, reducing the efficiency of energy transfer from the wind to the lake (Wetzel 2001). The majority of morphogenically meromictic lakes have a relative depth greater than 4% and a surface area less than 50 ha (Swanner et al. 2020). Although all four formation pathways are distinct, these pathways are not mutually exclusive and meromictic lakes often form through a combination of factors that reinforce one another (Hakala 2004).

Regardless of the mechanism of meromictic formation, the outcome is a permanently stratified lake that never mixes to the bottom. Thus, DO is never reintroduced to the monimolimnion like it is to the hypolimnion of holomictic lakes. Biological and chemical oxygen demand of the sediment and water column exceeds the oxygen supply, entrenching the monimolimnion in an anaerobic state (Beutel 2003; Boehrer et al. 2017). The low redox potential of the monimolimnion results in dramatically different water chemistry compared to the mixolimnion (Boehrer & Schultze 2008). For example, monimolimnetic waters commonly have high levels of hydrogen sulphide and dissolved metals (e.g., Fe^{+2}, Mn^{+2}) (Schultze et al. 2017). Subsequently, meromictic lakes develop drastically different ecosystems with unique bacterial communities that are adapted to thrive in this anaerobic and sulphuric environment (Zadereev et al. 2017). Furthermore, the anaerobic conditions result in the accumulation of nutrients through sedimentation from the mixolimnion and the process of internal phosphorus loading (section 1.4). This accumulation of nutrients in the monimolimnion directly influences lake water quality by altering whole-lake productivity.

1.4. Internal phosphorus loading

Under oxygenated conditions, many compounds and chemicals become trapped in the bottom sediment of lakes. However, if the hypolimnion or monimolimnion becomes anaerobic, a host of redox mediated reactions initiate the release of both toxic and algal limiting compounds from the sediment into the water column (Orihe et al. 2017). These reactions can increase algal growth, decrease water quality, and affect lake biota through acute and chronic toxicity (Boström et al. 1988; Spears et al. 2011).

The most important reaction in releasing algal nutrients and decreasing water quality is the process of internal phosphorus (P) loading. Although there are many pathways of internal P loading (Orihe et al. 2017), the common mechanism is the reduction of iron oxides in lake sediments (Einsele 1936). This process begins when P from the water column settles into the sediment and binds with Ferric (Fe^{3+}) oxyhydroxides under high DO conditions. If high DO concentrations are maintained, the P is trapped within the sediment. However, if the DO concentration decreases and the redox conditions at the sediment water interface become anaerobic, reductive dissolution occurs and the P dissolves back into the water (Einsele 1936).

Phosphorus is a common limiting nutrient for algae in lakes (Schindler 1977) and internal loading therefore results in increased primary production when nutrients reach the photic zone (Spears et al. 2011) through processes such as complete/partial water column mixing (Boehrer & Schultze 2008) or internal seiches (Ostrovsky et al. 1996; MacIntyre & Jellison 2001). Increased primary production subsequently increases respiration that further depletes hypolimnetic/monimolimnetic DO and facilitates more internal P loading (Boström et al. 1988). This positive feedback loop can cause eutrophication and enforce eutrophication previously initiated by external nutrient loading (Spears et al. 2011; Foley et al. 2012; North et al. 2014). If nutrient loading is sustained, the plankton assemblage of the lake can change, affecting water quality and the entire lake ecosystem (Ficke et al. 2007; North et al. 2014).

1.5. Study site

Lajoie Lake is part of the Bridge River watershed in southwest British Columbia, 90 km northwest from the town of Lillooet (Fig. 1). The Bridge River flows east in a Ushaped valley from its glacial origins in the Coast Mountains to its confluence with the Fraser River near Lillooet (Hill & Wright 1999). As the river flows east the biogeoclimatic zone reflects the orographic effect as it transitions from Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) to interior Douglas-fir (*Pseudotsuga menziesii*), and finally to Ponderosa pine (*Pinus ponderosa*) (Hill & Wright 1999). Today, the river is dammed for hydroelectricity in two locations. The Bridge River first flows into the Downton Reservoir, impounded in 1948 by the Lajoie Dam. From there, the river immediately flows into the Carpenter Reservoir, first created in 1948 by the Mission Dam and then raised to its current level in 1960 by the Terzaghi Dam (Hall et al. 2011). Lajoie Lake sits on bench above Downton Reservoir and collects runoff from six creeks draining the southeast side of Mount Penrose (Cascade Environmental Resource Group Ltd. 2018).

Figure 1. Location of Lajoie Lake.

Lajoie Lake is relatively small, covering 41 ha with a mean depth of 12 m and maximum depth of 23 m (Fig. 2) (British Columbia Ministry of Environment 1979). Mount Penrose towers over the lake to the northwest and hills rise 50 to 100 m from the lake surface (910 m above sea level) to the east, west and south. A small ridge separates Lajoie Lake from Gun Lake to the north. The lake is typical of those found in the Insular and Coast Mountain limnological region (Northcote & Larkin 1956). These lakes tend to have clear water due to the granitic nature of the surrounding bedrock, which leaches minimal dissolved solids into the water (Northcote & Larkin 1956). The result is lakes and streams with low nutrient content and oligotrophic conditions that provide desirable water quality for recreational and domestic use.

The Bridge River valley and Lajoie Lake is within the unceded territory of the of the Tŝilhqot'in Nation (Tŝilhqot'in National Government n.d.) and St'át'imc Nation (Xwísten n.d.). The St'át'imc people have used these lands since time immemorial for fishing, hunting, and agriculture until European colonization (Xwísten n.d.). After European colonization, mining boomed in the valley (Xwísten n.d.). Prospectors staked claims around Lajoie Lake, and although some mining occurred within the watershed, the lake was predominately used as a summer vacation site (Cascade Environmental Resource Group Ltd 2018). That practice persists today with all four properties surrounding the lake being used only in the summer months (Fig. 2). The lake is also used for recreational fishing with 2,000 rainbow trout stocked annually (Freshwater Fisheries Society of BC 2021). The only remaining industrial practice within Lajoie Lake's watershed is logging, which continues to occur northwest of the lake (Cascade Environmental Resource Group Ltd. 2018).

Figure 2. Lajoie Lake and the surrounding area.

Historically, Lajoie Lake was known for pristine water quality. Unfortunately, the long-time residents of the lake have noted deteriorating conditions since the 1970s (Cascade Environmental Resource Group Ltd. 2018). Their observations of increasing algal abundance and decreasing water clarity suggest Lajoie Lake is experiencing eutrophication. However, eutrophication requires an increased supply of nutrients and the lack of anthropogenic sources within the watershed suggests increased nutrient supply is not driving the observed changes to the lake. Previous surveys have consistently noted the lack of DO at depth, even early in the spring and in late autumn (BC Lake Stewardship Society 2008). Because Lajoie Lake freezes in the winter and should be dimictic, DO is expected to be abundant throughout the water column in early spring and late autumn when the lake should be circulating. Interestingly, the first formal survey conducted on Lajoie Lake in 1969 observed DO in the hypolimnion (Harding & Offin 1969). Together this suggests that the changes to Lajoie Lake could be the result of a rapid shift from dimixis to meromixis that eliminated oxygen supply and resulted in internal nutrient loading, rather than an increase in external nutrient loading causing low DO from increased demand.

If Lajoie Lake has transitioned to meromixis, it is likely morphogenically and/or topographically predisposed. Previous surveys of lake water quality found conductivity and other measures of solutes within an expected range, excluding the chemical formation of meromixis from crenogenic and ectogenic means. Likewise, the oligotrophic state of Lajoie Lake precludes endogenic formation as an initiating factor, but endogenic processes could be a reinforcing mechanism. Therefore, morphogenic formation is likely the key factor leading to meromixis. Of the two morphogenic formation pathways – topographic shielding and relative depth – topographic shielding is likely the main factor in any morphogenic meromixis. Lajoie Lake's relative depth calculated from its maximum depth of 23 m and surface area of 41 ha is 3.18% (Equation 1). This is less than the 4% benchmark noted in the literature (Swanner et al. 2020) and Lajoie Lake's relative depth is likely not impeding its ability to circulate. Therefore, topographic shielding is likely a contributing causal factor as Lajoie Lake's surrounding landscape, and its location at a sharp curve in the Bridge River valley, is potentially protecting it from prevailing winds. Ultimately, topographic shielding results in endogenic formation as all biological decomposition products remain in the monimolimnion and reinforce meromixis (Hakala 2004).

However, Lajoie Lake has always been topographically shielded and additional forcing was required to generate potential endogenic meromixis: climate change. Lajoie Lake is no exception to the influence of climate change and has undoubtably experienced the same trends of warming and extended stratification as lakes globally. Therefore, I hypothesize that topographic shielding predisposed the lake to a mixing regime change due to intensified and extended thermal stratification from a warming climate, ultimately resulting in degraded water quality. The goal of this study is to observationally test this hypothesis and synthesize the results to outline a restoration solution that is replicable for lakes similarly impacted.

2. Research Questions and Objectives

Issue: Despite no apparent increase in external nutrient inputs into Lajoie Lake, long-time residents have observed decreasing water quality in recent decades.

Goal: The overarching goal of this project is to determine the source of Lajoie Lake's water quality degradation and how to restore it.

Hypothesis: Lajoie Lake's calm conditions from topographic shielding predisposed it to a climatically induced mixing regime shift, ultimately resulting in anaerobic conditions, internal nutrient regeneration, and degraded water quality.

Research Questions: The hypothesis will be tested observationally by answering the following research questions.

Question 1: What is the stratification and annual circulation regime of Lajoie Lake and how does it influence hypolimnetic oxygen concentration?

> **H_A:** Lajoie Lake will exhibit a lack of, or partial, spring and/or autumn circulation and exhibit density stratification from ice-off until ice-on, resulting in some degree of hypolimnetic hypoxia.
>
> **H_0:** Lajoie Lake will circulate completely in the spring and autumn, demonstrating limited hypolimnetic oxygen consumption while thermally stratified.

Question 2: Does the shape of the lake basin topographically shield the water surface from wind and contribute to the lack of circulation?

> **H_A:** Lajoie lake will experience extended periods of calm conditions and low sustained wind speeds that are insufficient to overcome stratification.
>
> **H_0:** Lajoie Lake will experience regular winds and be subject to sustained wind speeds that are sufficient to overcome stratification.

3. Materials and Methods

3.1. Field Methods

Lajoie Lake was sampled either continuously, biweekly, or monthly dependent on the parameter measured and the time of year. Sampling occurred from 1 May 2022, one week after ice-off (23 April), until 18 November 2022, two weeks before ice-on (2 December). See Appendix B for a detailed sampling schedule.

Question 1: What is the stratification and annual circulation regime of Lajoie Lake and how does it influence hypolimnetic oxygen concentration?

To track the thermal depth profile of Lajoie Lake I installed a thermistor string consisting of 10 HOBO® Water Temp Pro v2 temperature loggers (model U22-001: ± 0.21 °C accuracy and 0.02 °C resolution). The thermistor string was constructed prior to deployment and consisted of two anchoring blocks, a 1.3-meter section of chain, rope, and two buoys. The chain attached to the rope ensured that the thermistors remained at the same depth during fluctuations in water level. Thermistors were attached to the rope with cable ties at 1, 3, 5, 7, 9, 11, 13, 15, 18, and 22 meters of depth.

I deployed the thermistor string in the deepest point of the lake at N 50.836766, W 122.906761 (Fig. 3) on 2 June 2022 and it began collecting data at 15:00. I programmed the sampling interval of the temperature loggers to maximize the battery life and data storage, while still being frequent enough to detect and analyse any internal seiches. Internal seiches are a natural phenomenon caused by sustained winds and are characterized by oscillations of the water layers at the density gradient (Spigel & Imberger 1980). The theoretical period of internal seiches was calculated as:

$$T = \frac{2L}{\sqrt{\frac{g(p_h - p_e)}{{p_h}/{d_h} + {p_e}/{d_e}}}} \qquad (2)$$

Where L is the length of lake along the wind axis, g is gravity, p is the density of the hypolimnion (h) and epilimnion (e), and d is the depth of the hypolimnion and epilimnion (Spigel & Imberger 1980). From L = 950 m, p_h = 0.9997 g/cm^3, p_e = 0.9982 g/cm^3, d_h =

14 m, and d_e = 5 m the period was estimated at 2.2 hours. Thus, the data loggers sampled the current water temperature every 30 minutes. I retrieved the thermistor string at 14:00 on 18 November 2022.

To capture the thermal profile of the lake prior to installing the thermistor string, I collected profiles using a YSI Pro2030 at the same location as the thermistor string (Fig.3). I sampled the DO profile simultaneously with all temperature profiles. I took measurements at 0.5 and 1 meters and then at 1-meter intervals until 24 meters. I sampled every two weeks beginning on 1 May 2022. After 28 June, when all remote loggers were deployed and confirmed to be operational, I continued to take thermal profiles monthly to provide backup data should the thermistors fail. Additionally, a member of the Lajoie Lake Resident Association (Troy Van Loon) profiled the lake weekly from 10 June onwards.

Finally, I collected depth profiles of specific conductance with the YSI Pro2030 concurrently with DO and temperature profiles. Specific conductance measures the electrical conductivity of the water standardized to 25 °C. It is a useful indicator of relative water chemical content and can reveal the chemical gradient expected in meromixis (Boehrer et al. 2017). Additionally, it is a proxy for total dissolved solids (TDS), which I used it to refine my estimates of water density in section 3.2 (Williams 1966).

Figure 3. Lajoie Lake monitoring locations.

Question 2: Does the shape of the lake basin topographically shield the water surface from wind and contribute to the lack of circulation?

To monitor the local wind speed, wind direction, and air temperature I installed a weather station on the north shore of the lake at N 50.839949, W 122.904596 (Fig. 3). Wind speed was measured with a HOBO® Wind Speed Smart Sensor (model S-WSB-M003: ±1.1 m/s accuracy, 0.5 m/s resolution, ≤ 1 m/s starting threshold) and wind direction was measured with a HOBO® Wind Direction Smart Sensor (model S-WDA-M003: ±5 degrees accuracy, 1.4 degrees resolution, 1 m/s starting threshold). Ambient air temperature was measured using a HOBO® 12-Bit Temperature Smart Sensor (model S-TMB-M0xx: ± 0.2 °C accuracy and 0.03 °C resolution) housed inside a solar radiation shield. All sensors were mounted on a HOBO 3-Meter Tripod Kit (model M-TPA-KIT) and data was logged using a HOBO® Micro Station (model H21-USB).

All weather parameters logged every 10 minutes. The station sampled wind direction and speed every 3 seconds, but it recorded the 10-minute average to simplify data analysis and to prevent maxing out the data storage. The maximum gust speed was also recorded over the 10-minute interval. The HOBO® Micro Station performs unit vector averaging to produce the average wind direction over the logging interval. The temperature sensor measured the current air temperature at the 10-minute interval.

Additionally, I recorded current weather information with a Kestrel® 3500 Pocket Weather Meter while collecting lake temperature and oxygen profiles. This provided backup data in the event of technological failures. I measured the current air temperature in a shaded and calm spot. To obtain average wind speed and max wind speed, I held the Kestrel above any interference while on the water for 1-minute. I estimated the average wind direction with a compass. In addition, I measured the fetch distance across the lake along this wind axis using Vortex® Fury HD 5000 10x42mm Rangefinding Binoculars.

Supplemental data and observations: Are there any other indicators of eutrophication, anoxia, and a mixing regime shift?

To supplement the above data, I collected two measures of water clarity and sampled for olfactory and visual indicators of anaerobia. I measured the Secchi depth each sampling trip (Appendix B) and supplemented this by measuring water turbidity at

0.5 metres with a LaMotte 2020we Turbidimeter. Furthermore, I assessed both the bottom lake sediment and the hypolimnetic waters for the presence of hydrogen sulphide. The sediment was retrieved attached to an anchor and the water sample was collected with a horizontal Van Dorn sampler at 15 m of depth.

3.2. Data summary and analysis

I performed all data summary and analysis in R (R Core Team 2022). I used the rLakeAnalyzer package (Winslow et al. 2019) to analyse water temperature profiles and the Openair package (Carslaw & Ropkins 2012) to analyse the weather data.

To assess the thermal stability of the lake, I calculated the Schmidt Stability Index (SSI) for each thermal profile collected with the thermistor string. SSI is a derived index that quantifies the amount of energy it would take to circulate a stratified water body in joules per meter squared (J/m^2) under ideal conditions (no heat gain or convective heat loss) (Idso 1973). The higher the SSI, the higher the strength of stratification. rLakeAnalyzer uses Idso's refined method for this calculation (Idso 1973) and only accounts for the thermal density properties of the water (Winslow et al. 2019). Therefore, this is only an estimate of the total strength of stratification that does not account for the influence of dissolved solids on density. I applied a common SSI threshold – 30 J/m^2 – to determine the onset and end of thermal stratification (Engelhardt & Kirillin 2014). SSI values less than 30 J/m^2 imply weak stratification, and vertical mixing is possible. For SSI calculation, I used lake bathymetry generously supplied by Northwest Hydraulic Consultants Ltd. (Fig. 4).

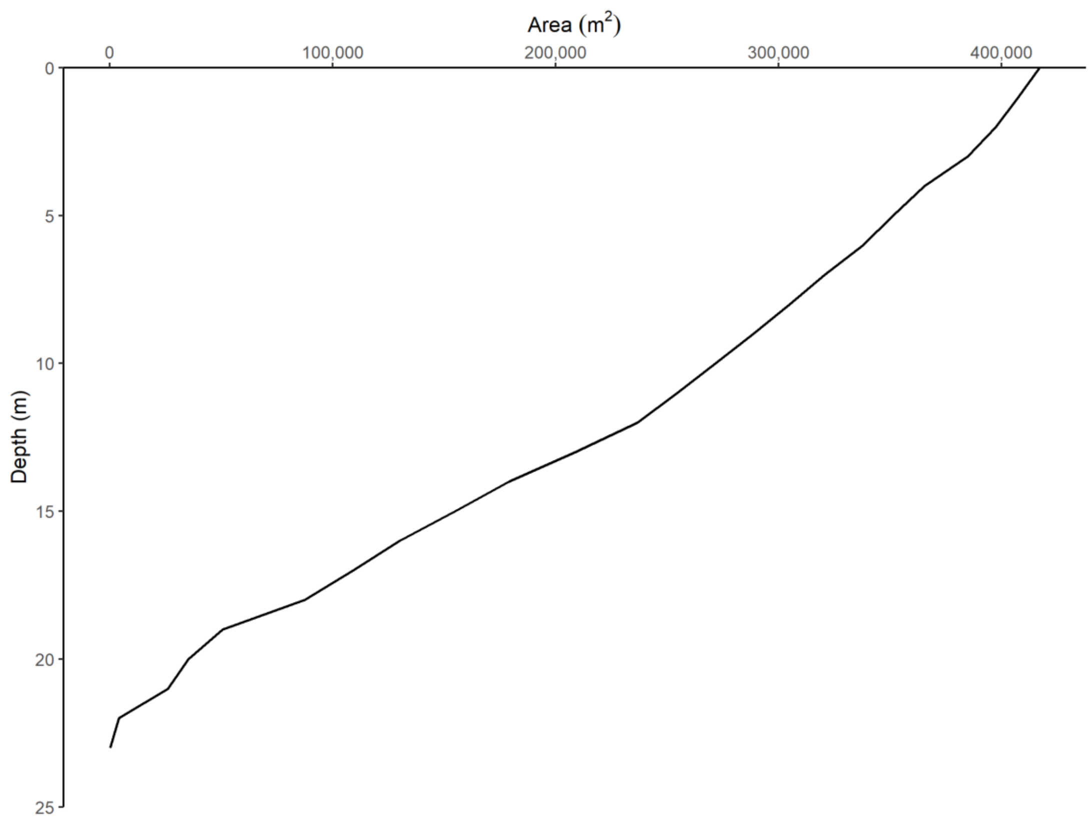

Figure 4. Hypsometric curve of Lajoie Lake.
The hypsometric curve displays the surface area at each 1 m depth increment and was provided by Northwest Hydraulic Consultants Ltd.

To estimate the influence of TDS on water density, I multiplied the specific conductance of each water layer by 0.65 to estimate TDS in mg/L (Williams 1966). I added this value to the water density value calculated by rLakeAnalyzer, which assumes pure water at the given temperature (Winslow et al. 2019). I then plotted the derived depth profiles of density from each sampling trip to compare the relative influence that water temperature and dissolved solids had on the density profiles.

In addition to calculating SSI, I used rLakeAnalyzer to calculate the depth to the thermocline. The package defines this as the point in the water column with the steepest density gradient based on water temperature (Winslow et al. 2019). To visualise how the water temperature profile changed over the ice-off season, I used rLakeAnalyzer to plot the thermistor data as a heat map. Furthermore, I plotted all the DO and temperature profiles collected throughout the sampling season to visualise how the trends evolved over time. Finally, I plotted each specific conductance profile to determine the location of any chemical gradients in the water column.

To summarise weather data and evaluate trends, I used the Openair package in R (Carslaw & Ropkins 2012). This package plots wind rose figures that allow for visualisation of prevalent wind direction and speeds. These plots are a form of histogram that is displayed on a compass rose. Wind direction observations are binned in 10-degree intervals and displayed as a percent of total observations. Each bin is further divided into the proportion of measurements recorded at different speed intervals. Additionally, the package calculates mean wind speed (including zero counts) and percentage of time with zero wind. I created multiple plots to assess average wind trends during the entire ice-off season, trends in wind speed and direction monthly, and patterns in wind speed and direction diurnally.

Upon precursory data exploration, it was apparent that internal waves were present throughout the 2022 ice-off season. To characterise these internal seiches, I plotted the water temperature from each thermistor over a select time-period: 1 July to 3 July. Not all thermistors were plotted to improve figure clarity. To assess the magnitude and period of any internal waves detected, I then plotted the 9 m thermistor data over this timespan. I also combined these figures with wind trends over the same period to illustrate the connection of internal waves to wind energy.

To determine whether Lajoie Lake receives enough wind energy to vertically mix the water column in autumn, I utilized the Wedderburn number (W) calculated with the rLakeAnalyzer package. W is a dimensionless parameter that represents the ratio between the wind and barotropic forces and baroclinic forces (Spigel & Imberger 1980; Imberger & Hamblin 1982). It is calculated as follows:

$$W = \frac{\left(\frac{g(p_h - p_e){h_e}^2}{p_e}\right)}{{u_*}^2 L} \qquad (3)$$

Where g is gravity, p_h is the hypolimnetic density, p_e is the epilimnetic density, h_e is the epilimnetic depth, u_* is the water-side shear velocity, and L is the length of the lake which the wind force is acting. Thresholds have been put forth by Gibbs & Howard-Williams (2018) to determine if wind mixing is occurring using W (Table 1). However, a more conservative threshold states that W values less than one indicate vertical mixing of the water column (Imberger & Hamblin 1982). I considered both thresholds to determine if Lajoie Lake is topographically shielded.

Table 1. Thresholds for wind induced mixing using the Wedderburn number from Gibbs & Howard (2018).

Wedderburn number threshold	Mixing condition	Threshold in Lajoie given 18 November conditions
$W > (L/4)h_e$	Strong stratification and no mixing.	$W > 2737.5$
$½ < W < (L/4)h_e$	Mixing forces are strong, but thermocline persists and most mixing occurs within the surface layer.	$½ < W < 2737.5$
$h_e/L < W < ½$	Wind is strong enough to induce a high degree of mixing.	$0.02 < W < ½$
$W < h_e/L$	Wind forces induce complete circulation	$W < 0.02$

L is the length of the basin on the axis the wind is blowing (730 m), and h_e is the height of the epilimnion (15 m).

To determine if autumn wind is sufficient to induce mixing, I first isolated the potential mixing period based on thermal stratification using the 30 J/m^2 SSI threshold. I then calculated the average wind speeds (with and without zero counts) during this thermally destratified period. Because average wind speeds may not account for briefer periods of sustained wind, I additionally isolated the highest average wind speed sustained for 20 minutes. This acts as an upper threshold for wind energy during this period. Using these wind speeds, I calculated W with rLakeAnalyzer and stratification conditions on 18 November with the density contribution of TDS accounted for as described above.

To further demonstrate the topographic shielding of Lajoie Lake, I found the wind conditions that could generate a W value that would meet the threshold for mixing. I then searched for occurrences of this wind speed throughout the entire recorded period at Lajoie Lake. If the wind speeds that could mix Lajoie are never or rarely present, even outside the destratified period, it provides strong evidence for the role of topographic shielding.

4. Results

4.1. Stratification

Lajoie Lake exhibited stratification rapidly after ice-off and throughout the summer season. One week after the lake was ice free, the water column was thermally stratified with less than 1 mg/L of DO in the hypolimnion (Fig. 5). This indicates that no spring turnover occurred. Thermal stratification strength increased throughout the summer to a peak of 555.6 J/m^2 on August 25 (Fig. 6). SSI declined into autumn and fell below 30 J/m^2 on 2 November. Trends in water temperature matched trends in SSI as they are directly related. As expected, water heat content increased throughout the summer and began declining late summer (Fig. 7). The depth to the thermocline deepened gradually throughout the season, then began rapidly deepening in September and October as convective cooling progressed (Fig. 8).

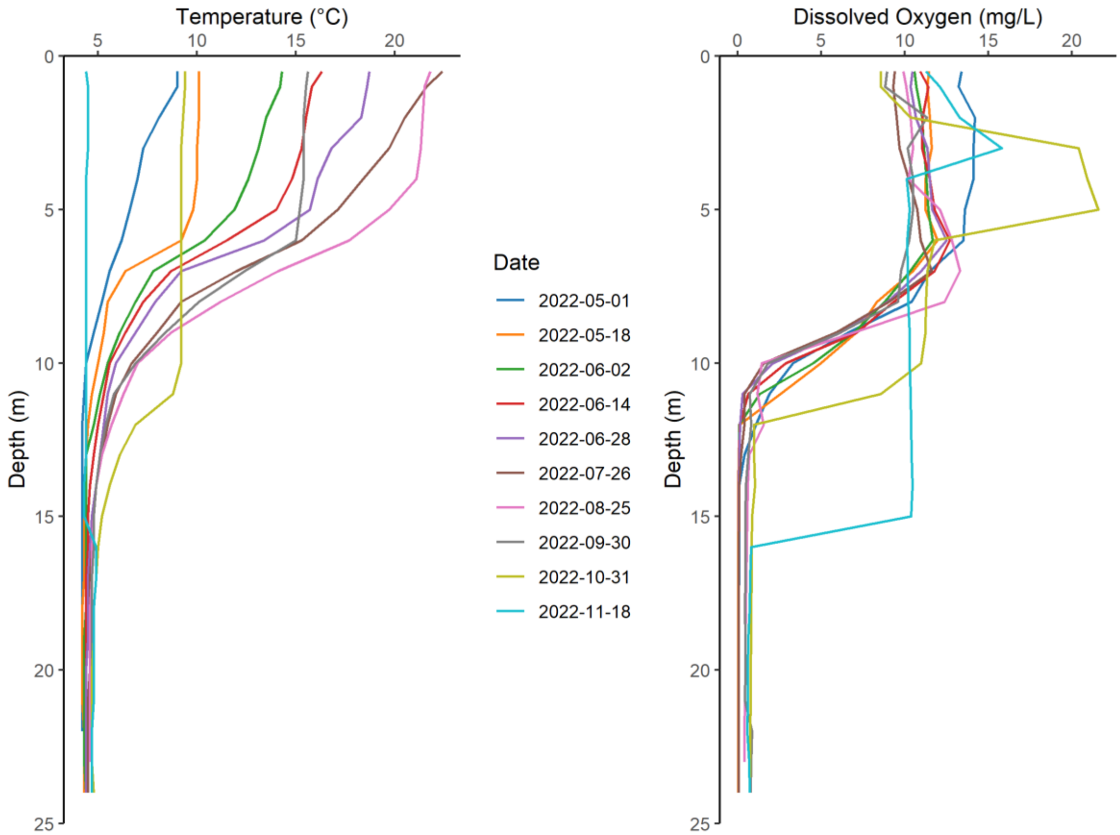

Figure 5. Depth profiles of Lajoie Lake's water temperature and dissolved oxygen during the 2022 ice-off season.

Water temperate and dissolved oxygen was measured at 0.5 and 1 meters, and then at 1-meter intervals during the 2022 ice-off season from 1 May to 18 November.

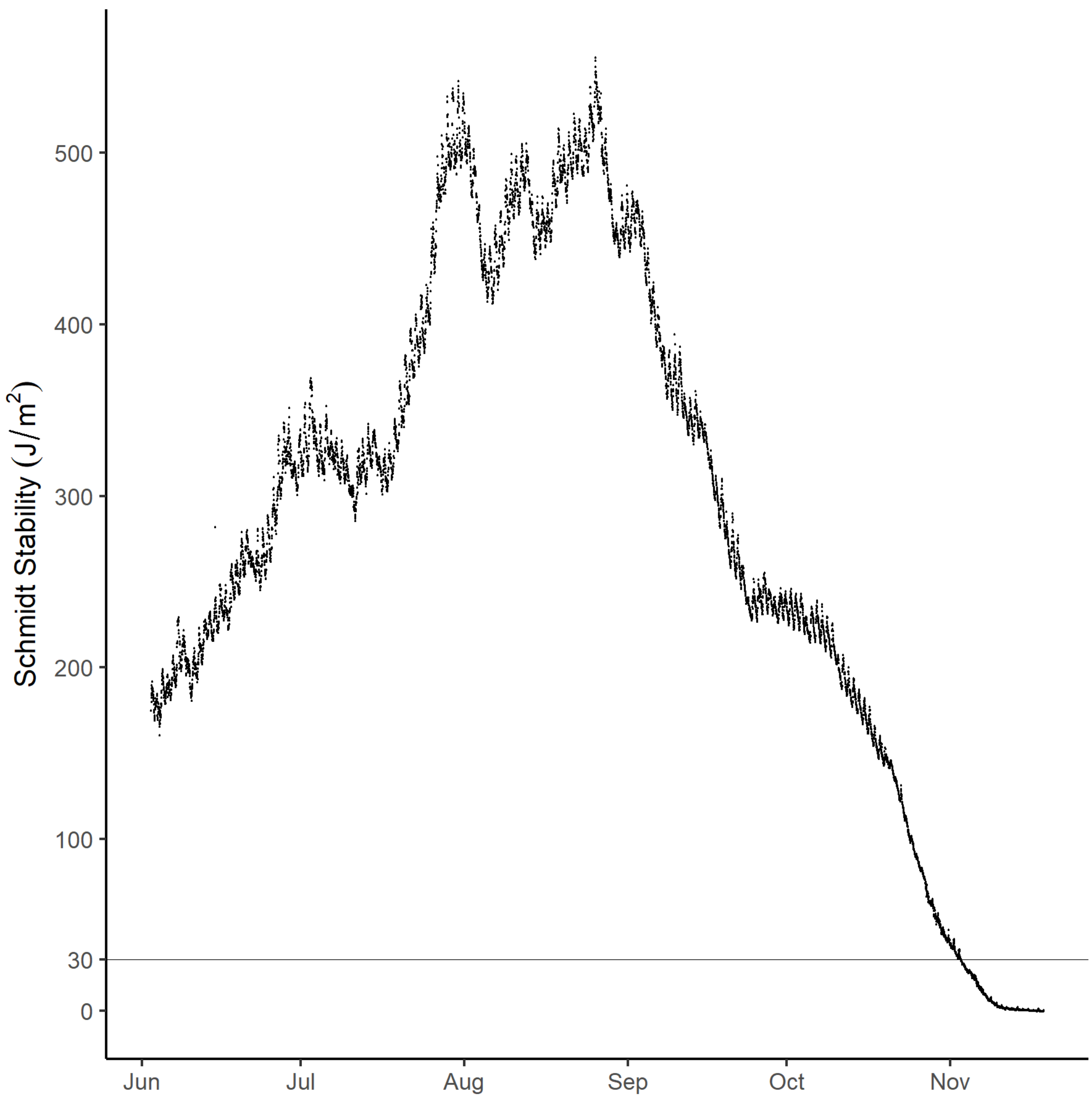

Figure 6. The Schmidt Stability of Lajoie Lake from 2 June to 18 November 18, 2022.

Values are calculated using the rLakeAnalyzer package in R and are derived from 10 temperature loggers (1, 3, 5, 7, 9, 11, 13, 15, 18, and 22 meters of depth) that sampled the water column temperature every 30 minutes. Higher stability values indicate stronger thermal stratification and a higher resistance to mixing. The horizontal line at 30 J/m^2 is a threshold for stratification, beneath which the water column is potentially subject to mixing.

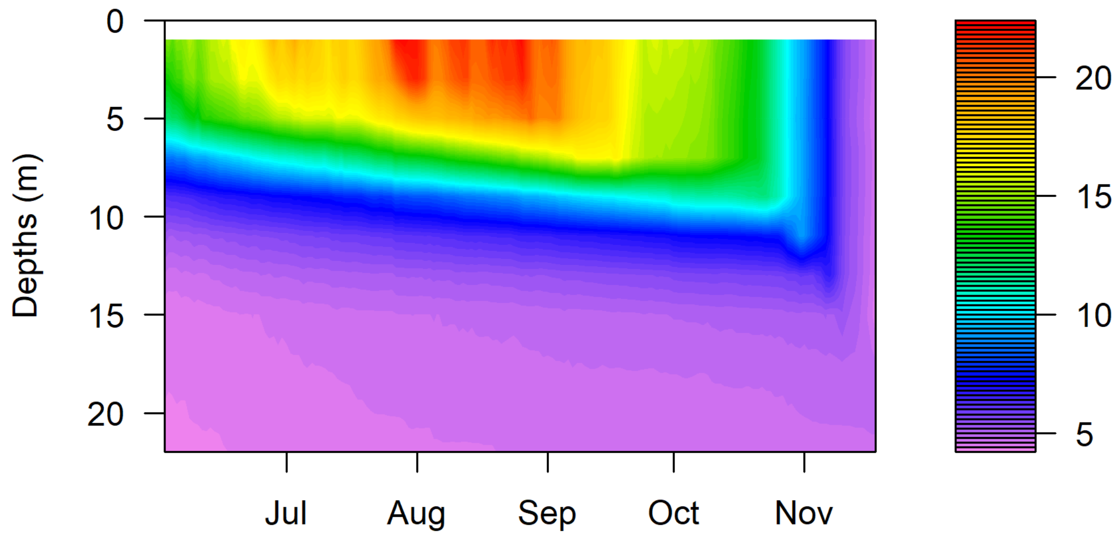

Figure 7. Heatmap of Lajoie Lake's water column from 2 June to 18 November 2022.

The heatmap was created using the rLakeAnalzyer package and data from 10 temperature loggers placed at 1, 3, 5, 7, 9, 11, 13, 15, 18, and 22 meters of depth. Water temperature was logged every 30 minutes and daily mean of each layer was used to generate the plot.

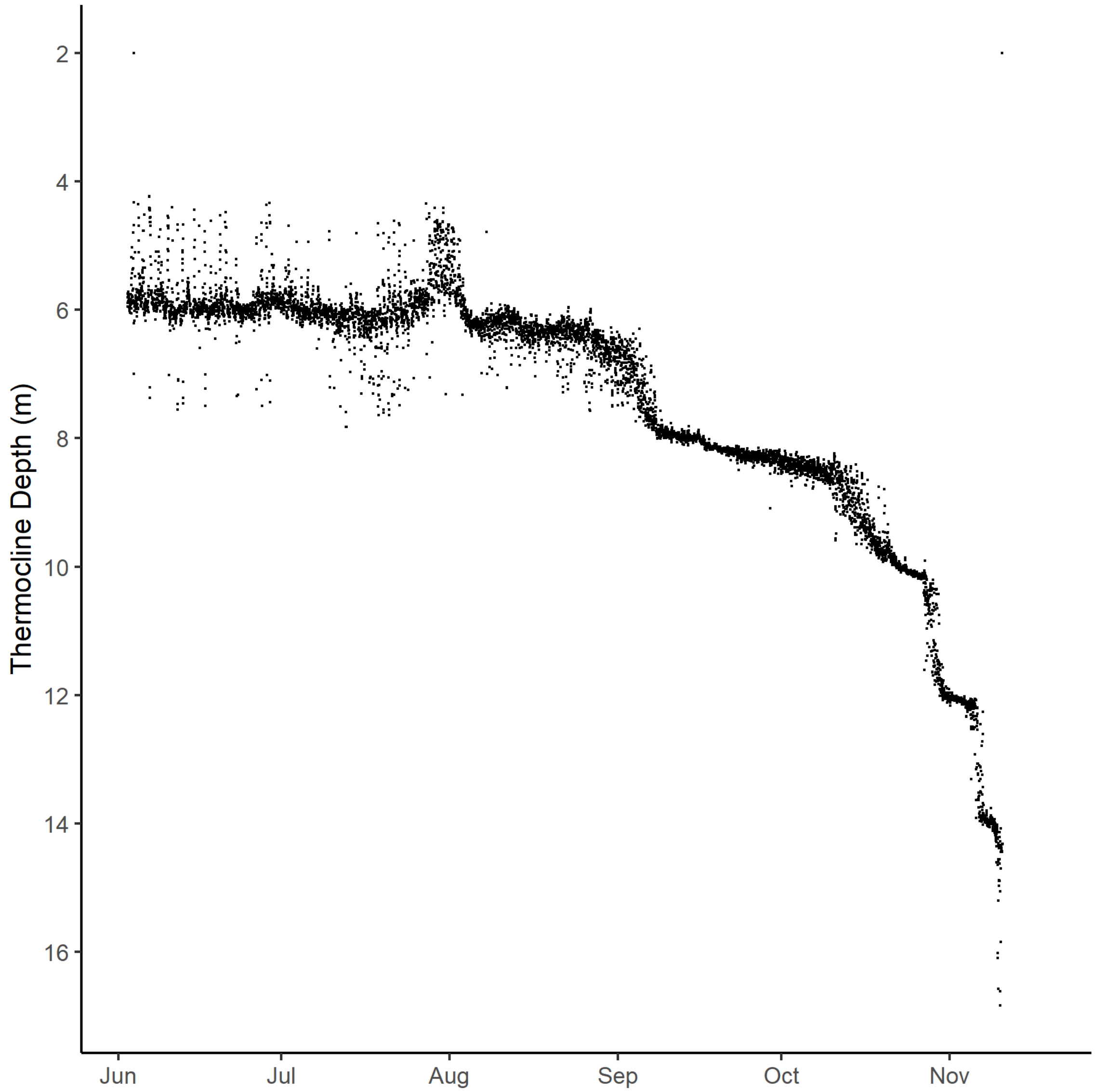

Figure 8. The depth to the thermocline of Lajoie Lake from 2 June to 18 November 2022.
Values are calculated using the rLakeAnalyzer package in R and are derived from 10 temperature loggers (1, 3, 5, 7, 9, 11, 13, 15, 18, and 22 meters of depth) that sampled the water column temperature every 30 minutes. Thermocline depth is defined as the depth where the water density gradient due to thermal properties is the steepest.

Profiles of specific conductance indicate that chemical gradients are present in the water column (Fig. 9). During the summer (June to August), an initial gradient occurs between 5 and 7 m, matching the location of the thermocline (Fig. 8); a second gradient begins around 21 m. The top gradient moves during the autumn, roughly following the deepening of the thermocline. This indicates that the chemical composition of the water column is contributing to the density gradients and reinforcing stratification. This contribution is stabilizing the water column once thermal stratification has broken down and why the 18 November profile displays warmer water at depth (Fig. 5). This would be impossible if chemical components were not influencing water density. However, the chemical influence on water density is minimal relative to the thermal effects (Fig. 10). The density profile on 18 November appears uniform in comparison to all other profiles, but when viewed alone the density gradient is clear (Fig. 10). This demonstrates that while thermal stratification dominates throughout the season and determines the location of the pycnocline, it is this slight chemocline that prevents Lajoie Lake from mixing at all depths.

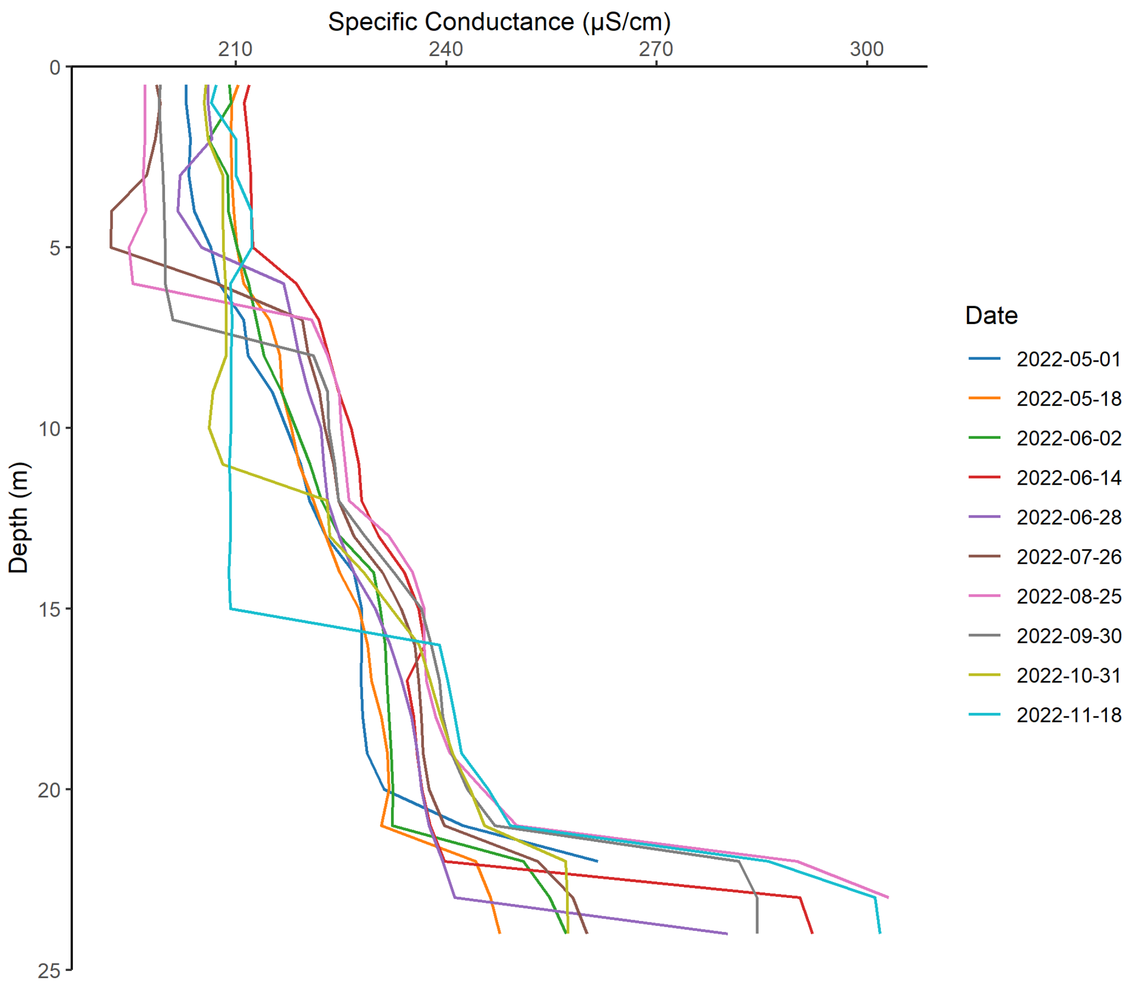

Figure 9. Depth profiles of Lajoie Lake's specific conductance.
Specific conductance is defined as water electrical conductivity corrected to a 25 °C standard. It was measured at 0.5 and 1 meters, and then at 1-meter intervals during the 2022 ice-off season from 1 May to 18 November.

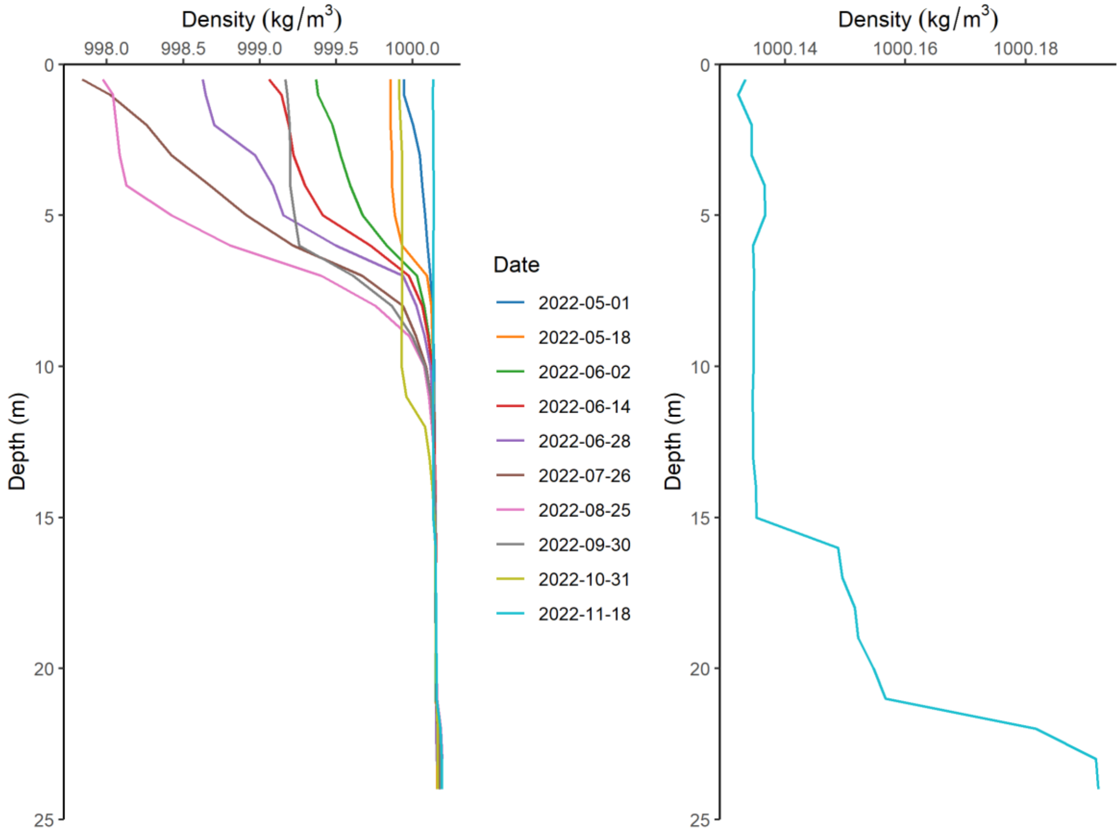

Figure 10. Depth profiles of Lajoie Lake's water density.
Water density was estimated using rLakeAnalyzer's water density calculator, which calculates density from temperature assuming pure fresh water. To refine the estimate and account for chemical density inputs, specific conductance was multiplied by 0.65 to convert it to total dissolved solids (mg/L) and then added to the pure water density. Profiles of specific conductance and temperature were measured at 0.5 and 1 meters, and then at 1-meter intervals during the 2022 ice-off season from 1 May to 18 November.

Hypolimnetic conditions were anoxic in all profiles. The DO in the hypolimnion varied slightly between sampling trips, but this is likely attributed to variations in calibration accuracy rather than true changes in DO. Regardless, hypolimnetic DO remained below 1 mg/L in all profiles (Fig. 5). Additionally, the bottom sediments were dark and smelled strongly of hydrogen sulphide, an indicator of anaerobic conditions (Greenbank 1945). The epilimnion was well oxygenated and profiles often displayed a metalimnetic oxygen maximum (Fig. 5): an increase in DO at the top of the thermocline caused by primary producers and physical processes (Wilkinson et al. 2015). Additionally, purple sulphur bacteria (PSB) were found on the thermistor string upon its retrieval (Fig. 11). I noted colonies of the bacteria on the temperature loggers at 13 m and 15 m, but I could not detect the bacteria in water samples collected with a Van Dorn bottle at these depths. PSB exist at these depths because they require reduced forms of sulphur and sufficient light for photosynthesis (Camacho 2009). Therefore, they persist in the narrow water column band where both conditions are satisfied. The entrainment and oxygenation of hypolimnetic waters during November (Fig. 8) likely reduced PSB abundance as reduced sulphur was oxidized, potentially explaining why PSB were not detected in the Van Dorn samples.

Figure 11. Purple sulphur bacteria on the 15 m temperature logger.
Purple sulphur bacteria on the 15-meter temperature logger are shown upon its removal from the water column on 18 November 2022. Similar presence was noted on the 13-meter temperature logger.

4.2. Meteorology

From 14 June to 18 November the mean wind speed was 0.8 m/s, with calm conditions being present 59.6% of the time (Fig. 12). When conditions were not calm, the wind predominantly came from between the west, along the Bridge River valley, and the south (Fig. 12). However, the wind direction and prevalence depended on the time of day. Days were windier (49.8% calm) than nights (71.6% calm) and westerly wind was more prevalent during the day (Fig. 13). The general wind pattern was calm nights and mornings, with wind becoming stronger from the late afternoon until the late evening. An example of this pattern is displayed in Figure 17 in section 4.3. This indicates a katabatic cooling effect within the valley. Katabatic winds are commonly generated in glacially headed valleys in which upslope air cools faster than downslope air and the subsequent density difference creates outflow winds (Munro 2005).

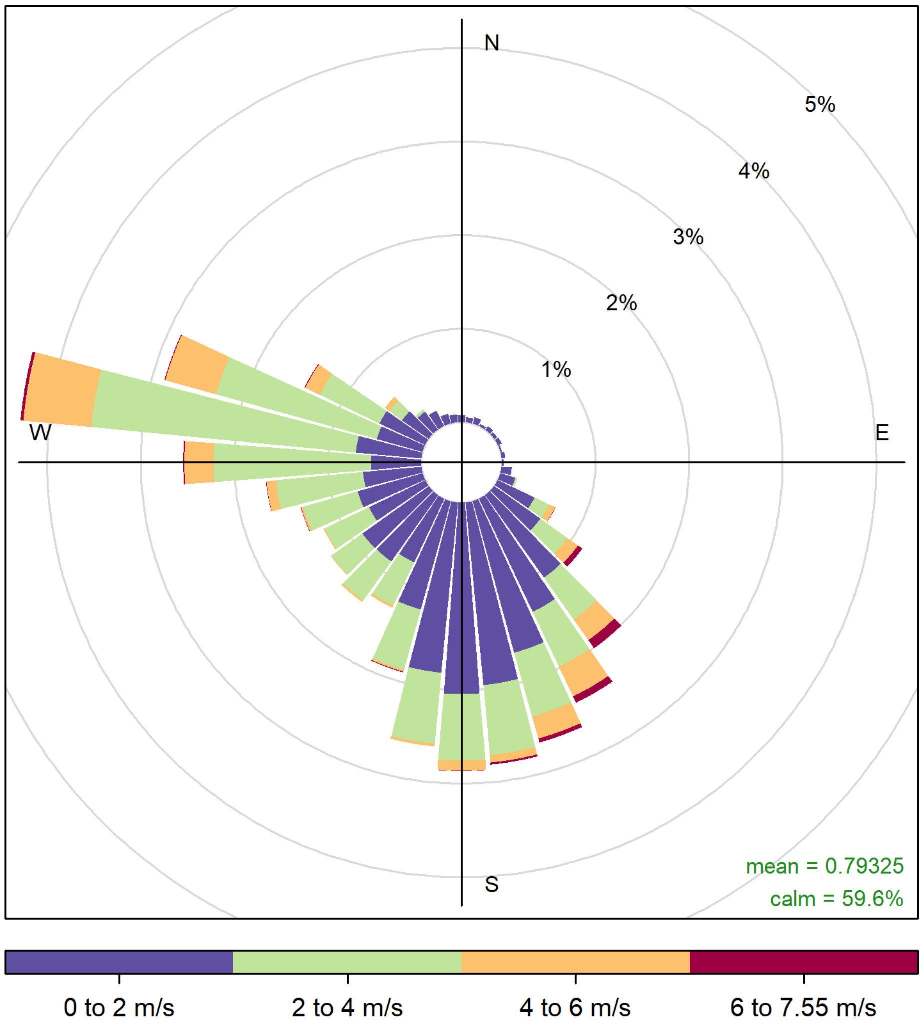

Figure 12. Wind rose depicting wind patterns on Lajoie Lake from 14 June to 18 November 2022.

Wedges represent the frequency of counts within a 10-degree window as a percentage. Colours represent the wind speed of those counts. Average wind speed and direction was sampled every 3 seconds and the 10-minute average was logged.

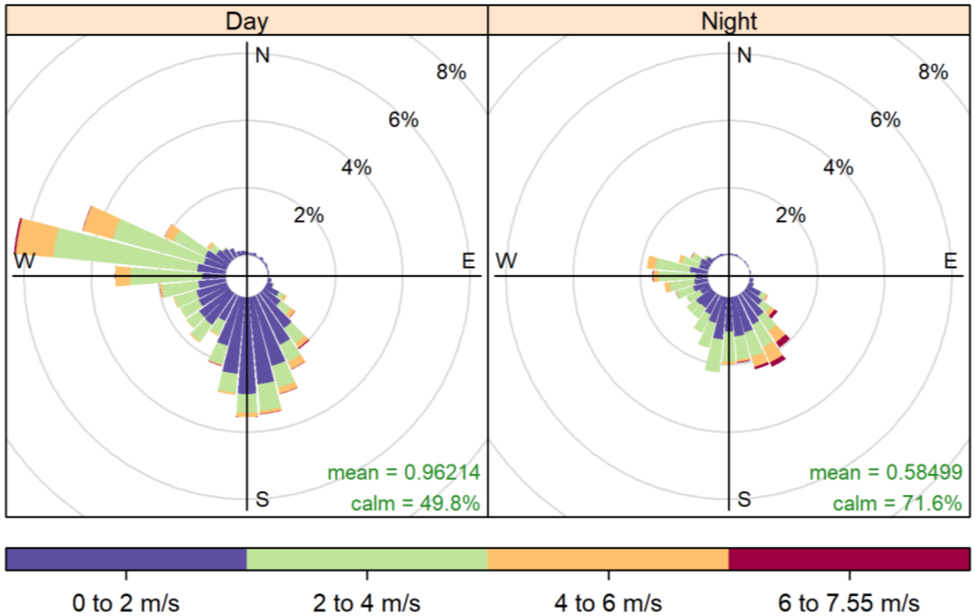

Figure 13. Wind rose depicting diurnal wind patterns on Lajoie Lake from 14 June to 18 November 2022.
Wedges represent the frequency of counts within a 10-degree window as a percentage. Colours represent the wind speed of those counts. Average wind speed and direction was sampled every 3 seconds and the 10-minute average was logged.

Wind patterns were further influenced by the time of year (Fig. 14). Mean wind speed was 0.9 m/s, 1.3 m/s, 0.9 m/s, 0.6 m/s, 0.6 m/s, and 0.3 m/s in June to November, respectively. Windy conditions were most common in July, with calm conditions occurring 49.6%, 43%, 52.8%, 65.5%, 73.4%, and 74.5% of the time in June to November, respectively. Diurnal wind patterns persisted through each month, but the difference between night and day became less pronounced beginning in September (Fig. 15). Additionally, southerly winds became more prevalent than westerly winds in autumn as the katabatic forces weakened with declining solar heating (Fig. 15).

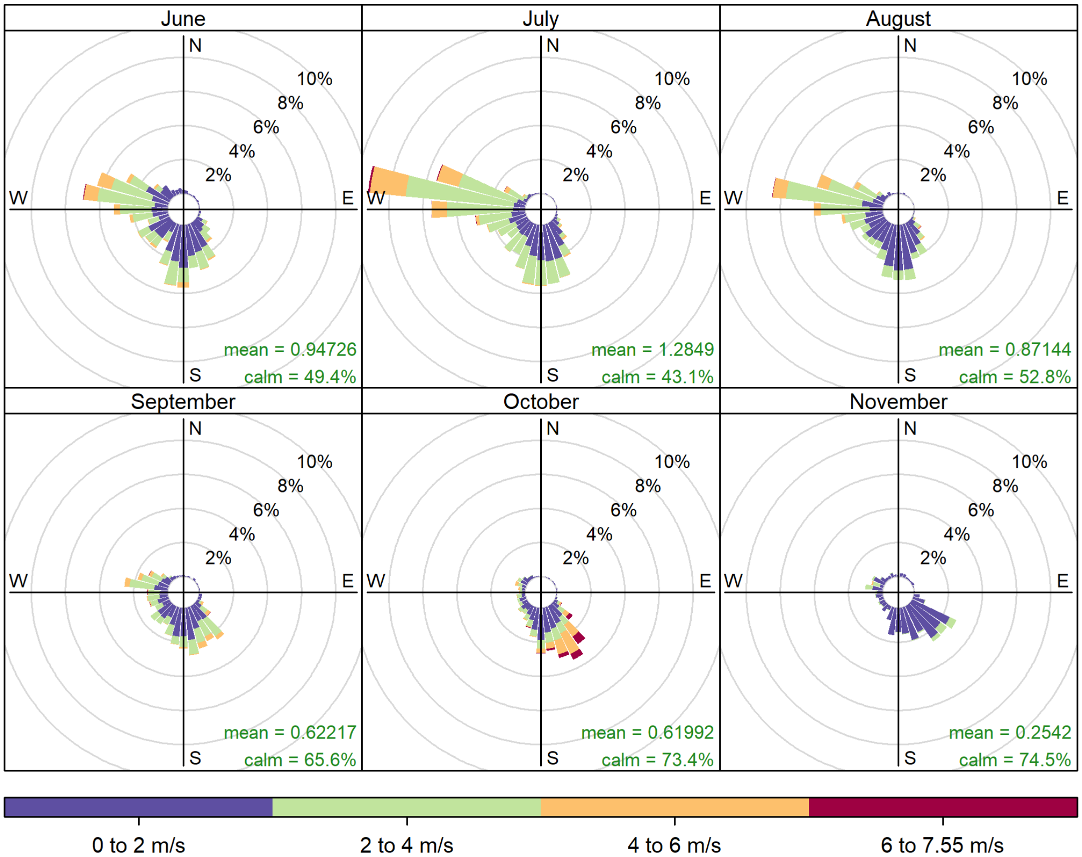

Figure 14. Wind rose depicting monthly patterns on Lajoie Lake from 14 June to 18 November 2022.

Wedges represent the frequency of counts within a 10-degree window as a percentage. Colours represent the wind speed of those counts. Average wind speed and direction was sampled every 3 seconds and the 10-minute average was logged.

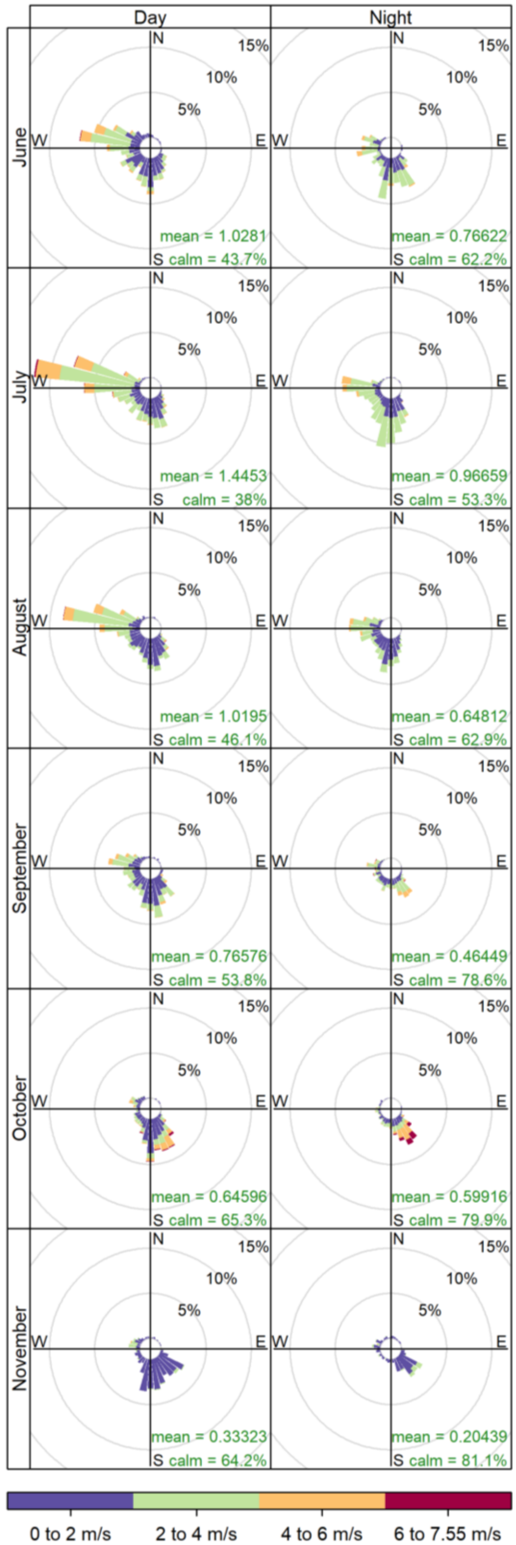

Figure 15. Wind rose depicting diurnal wind patterns by month on Lajoie Lake from 14 June to 18 November 2022.

Wedges represent the frequency of counts within a 10-degree window as a percentage. Colours represent the wind speed of those counts. Average wind speed and direction was sampled every 3 seconds and the 10-minute average was logged.

4.3. Internal seiches

Internal seiches are present in Lajoie Lake, especially during the summer months (June to August) as a direct result of the katabatic winds. Waves are detectable from 5 m to 15 m in the water column (Fig. 16). Water temperature fluctuations within the epilimnion are predominantly influenced by solar forcing, but influence from internal waves is detectable as shallow as 5 m. There is no detectable influence of waves at 22 m, but their influence is observed at 15 m. The depth of wave penetration could influence the location of the second chemical gradient observed below 20 m (Fig. 9). The period of the waves is highly variable as each wind event generates more seiche activity and multi-nodal seiches are potentially occurring (Fig. 17). Nevertheless, the period of the seiches is approximately 4 hours.

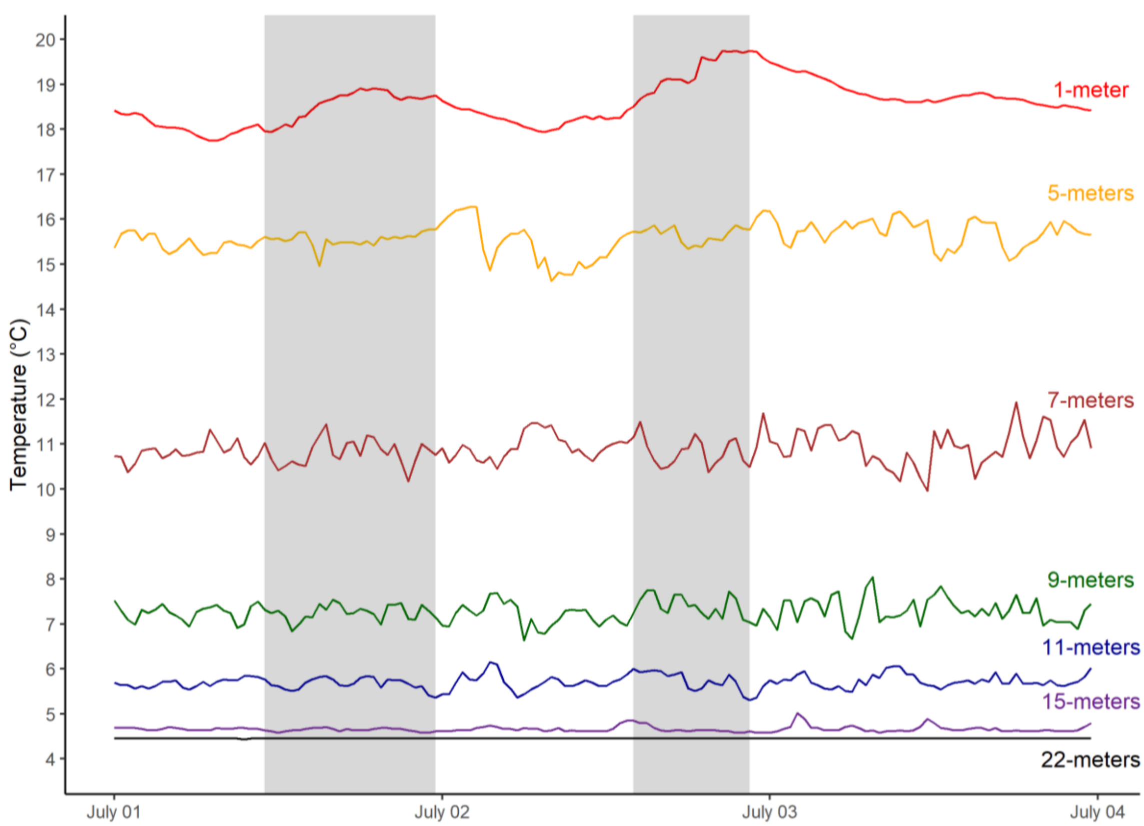

Figure 16. Internal seiche activity throughout Lajoie Lake's water column from 1 July to 3 July 2022.
Water temperature was collected from temperature loggers suspended at the given depth. Not all loggers are displayed for clarity. Current water temperature was logged every 30 minutes. Grey rectangles display periods of sustained wind.

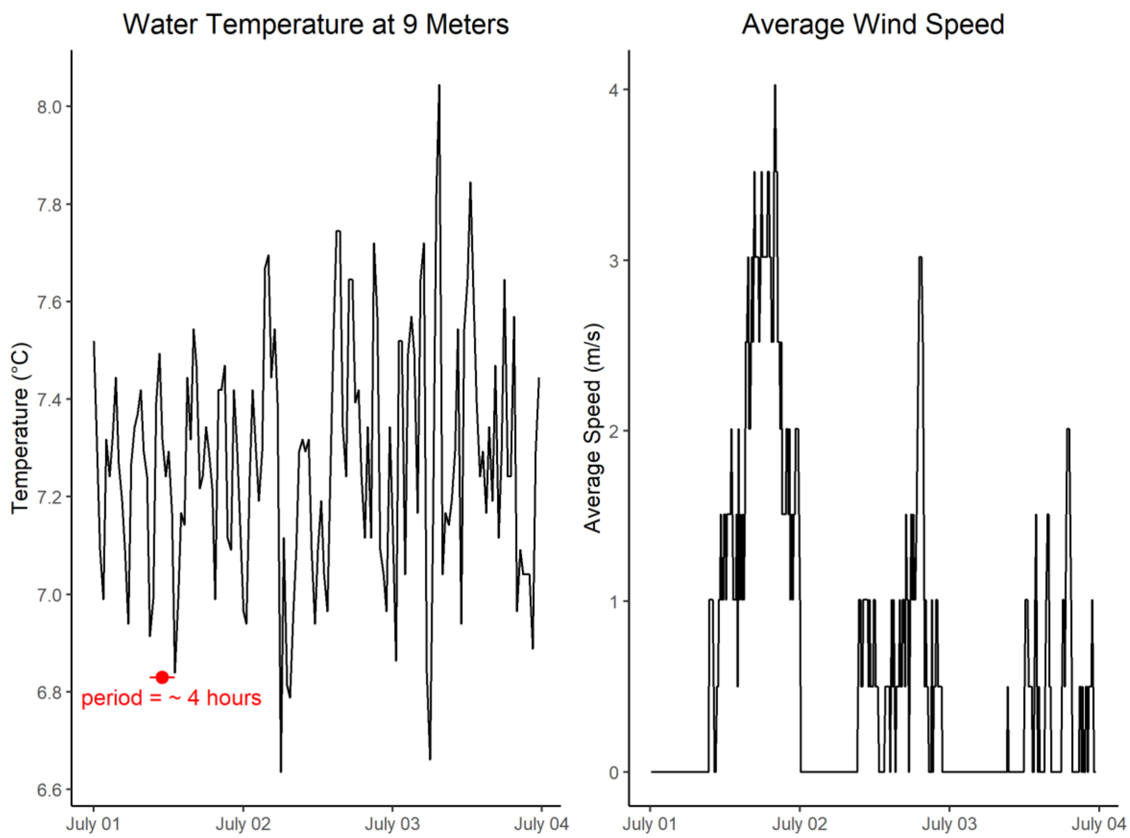

Figure 17. Internal seiche activity in Lajoie Lake at 9 meters of depth, and average wind speed, from 1 July to 3 July 2022.
Water temperature was collected from a temperature logger suspended at 9 meters and the current water temperature was logged every 30 minutes. Average wind speed was sampled every 3 seconds and the 10-minute average was logged.

4.4. Evidence of topographic shielding

During the recorded thermally destratified period in Lajoie Lake (2 November to 18 November), there were no wind speed scenarios that reduced W close to thresholds for mixing (Table 1). Conversely, based on these thresholds all wind speeds present during the destratification period were only strong enough to mix the surface layer (Table 2). Therefore, I used the more conservative threshold ($W < 1$) to determine the wind speed that would induce mixing. The closest value ($W = 4.35$) was produced by using the highest mean wind speeds sustained for 20 minutes (3.78 m/s). Even this wind speed was rare, only occurring on 5 November. To produce W less than 1 for Lajoie Lake given the density conditions on 18 November, a sustained wind of about 6 m/s is required. While these wind speeds were never recorded during the destratified period in Lajoie Lake, they were observed 89 times throughout 9 days during the entire weather station deployment. Interestingly, most of these high wind speeds were recorded from October 27-30, less than a week before the lake was considered thermally destratified. This suggests that if the lake was thermally destratified earlier, it may have mixed.

Table 2. Lajoie Lake wind speeds during the potential mixing window (2 to 18 November) and their associated Wedderburn number (W).

Scenario	Wind Speed (m/s)	W
Average wind speed (with zero counts)	0.26	882.85
Average wind speed (no zero counts)	1.00	61.02
Maximum 20-minute sustained wind speed	3.78	4.35
Minimum wind speed for W <1	6.00	0.98

W values were calculated using the rLakeAnalyzer package and equation 3 using the stratification conditions on 18 November (h_e = 15, p_e = 1000.135 kg/m^3, p_h = 1000.165 kg/m^3). Wind speed was sampled every 3 seconds and the 10-minute average logged. The surface area of the lake used to calculate W was 417 000 m^2.

5. Discussion

All evidence supports the hypothesis that Lajoie Lake is now in a meromictic state. The lack of hypolimnetic DO after the vernal mixing period and the persistent presence of a chemocline into the autumn mixing period both indicate that complete circulation did not occur during the 2022 ice-off season. Additionally, this detectable chemocline and the presence of purple sulphur bacteria indicate the lake has not circulated recently. Historical data noting the lack of hypolimnetic DO suggests that this state has persisted since at least 1991 (Cascade Environmental Resource Group Ltd. 2018). A survey conducted in 1969 found a high concentration of hypolimnetic DO (Harding & Offin 1969), demonstrating that the lake did circulate historically, and a survey in 1980 found hypoxic conditions (Caverly 1980). Therefore, the permanent shift in the mixing regime must have occurred before 1990 and likely began between 1970 and 1980. This timeline correlates to when residents began observing changes to the lake's water quality. While it is apparent the lake mixing regime has shifted, the question remains as to why and how.

With an apparent lack of anthropogenic causes, I hypothesized that climate change triggered the shift to meromixis, and that the surrounding topography predisposed it to this shift. While most meromictic lakes form through a strong salinity gradient, Lajoie Lake does not exhibit the extreme chemical stratification characteristic of these lakes (Walker & Likens 1975). Neither is Lajoie Lake solely morphogenically meromictic. These types of meromictic lakes are rare and usually the product of a high relative depth that restricts mixing (Walker & Likens 1975). But as discussed in section 1.5, Lajoie Lake's relative depth is below the threshold shown to resist mixing. Instead, the surrounding topography appears to limit the wind energy delivered to the lake during the fall mixing period and has left Lajoie Lake uniquely susceptible to intensified and lengthened stratification caused by climate change (Woolway & Merchant 2019).

Meromictic development in Lajoie Lake due to climate change is effectively the result of a shortened window of mixing opportunity. At the end of a lake's summer stratification period, a slight chemical gradient exists as solutes naturally accumulate at depth. However, the slight density gradient present after the breakdown of thermal stratification is weak and does not require significant wind energy to be overcome and fully mix the lake. The period between the breakdown of thermal stratification and freeze-over is the window during which wind will completely circulate the lake. However, climate change is shown to increase the duration of thermal stratification further into autumn (Woolway & Merchant 2019). If the freeze-over date is not equally impacted, then this longer stratification results in a reduced window for complete mixing to occur. This does not inhibit mixing on most lakes, as they receive ample wind energy to mix prior to freeze-over. However, with the limited wind Lajoie Lake receives, any reduction of the mixing window limits its probability of receiving enough wind to mix. Historically, Lajoie Lake would have received enough wind energy to mix fully or partially, but any year it did not the elevated concentration of solutes in the hypolimnion persisted. This generated a positive feedback loop of endogenic meromictic formation as each subsequent year without mixing reinforced the chemical gradient and resulted in more wind energy being required for mixing. As climate change progressed, this positive feedback loop was reinforced as the window for mixing to occur shrank, decreasing the likelihood of that wind event occurring. Ultimately, this feedback loop has pushed Lajoie Lake into a new stable state of topographic and climatically induced endogenic meromixis.

5.1. Implications of meromixis for water quality and lake ecology

The formation of meromixis accounts for the changes to lake water quality and biotic composition observed by residents. In summary, residents have witnessed increased productivity, decreased water clarity, and increased accumulation of organic matter in the littoral zone. Lake circulation is a major influencer of lake productivity (Wetzel 2001). Hypolimnetic waters naturally accumulate nutrients that are reintroduced to epilimnetic waters during turnover events, controlling the abundance and species composition of phytoplankton (Sommer 1985). Anaerobic hypolimnetic/monimolimnetic water amplifies this process through internal P loading (Orihe et al. 2017). However, meromictic lakes do not mix throughout their entire depth and many lakes turned meromictic observe a reduction in productivity as monimolimnetic waters effectively trap nutrients (Zadereev et al. 2017). This contrasts with Lajoie Lake, which has experienced the opposite effect.

Lajoie Lake's meromictic state causes its unexpected increase in productivity due to the behaviour of the chemocline. While the chemocline depth in meromictic lakes is largely stable, it can experience movement that enables some mixing between the monimolimnion and mixolimnion (Boehrer et al. 2017). The chemocline in Lajoie Lake experiences movement through two phenomena: internal seiches and seasonal migration. During the summer stratification period, anoxic conditions begin around 10 m deep. Figure 5 shows this boundary shift during autumn as convective mixing entrains the top of the monimolimnion, moving the oxycline and chemocline down to around 16 m (potentially progressing deeper). The volume of water entrained into the mixolimnion is approximately 141 744 m^3, or about 34% of the lake volume. Presumably this water is nutrient rich and increases the nutrient concentration of the mixolimnion, resulting in increased productivity the following spring and summer.

In addition to seasonal chemocline migration, internal waves also enable movement of nutrients across the chemocline. Although autumn wind is nearly non-existent, wind is common during the summer (June to August). During summer evenings (peaking in July), the katabatic winds blow consistently from the northwest along the Bridge River valley. The resultant internal seiches create turbulence across the chemocline that allows for solutes to cross the boundary (Ostrovsky et al. 1996; MacIntyre & Jellison 2001) For example, seiches in meromictic Mono Lake increase transport of the limiting nutrient from the monimolimnion by 53% (Bruce et al. 2008). The epilimnion of lakes are usually nutrient poor; thus, any additional nutrients are readily consumed by phototrophs, increasing overall lake productivity, and potentially altering the phytoplankton community composition (Ostrovsky et al. 1996; Pannard et al. 2011). In combination with chemocline migration, internal seiches in Lajoie Lake provide a pathway for internally regenerated monimolimnetic nutrients to enter the photic zone and results in the observed increased lake productivity.

Meromixis clearly impacts nutrient regeneration and phytoplankton abundance and composition, but its impact on food web structure and trophic interactions is uncertain. This is because meromictic lakes are rare, and their conditions are often unique (Hall & Northcote 2012). Additionally, studies on meromictic food webs are even rarer and most observe the lakes well after meromixis developed and thus cannot compare to a previous state (Zadereev et al. 2017). Nevertheless, there is some literature that sheds light on how meromixis may have altered the ecological structure of

Lajoie Lake and offers explanations for observed changes, such as the decline in fish size and numbers.

The biological composition and food web structure of lakes is influenced by meromixis directly through habitat loss and indirectly through altered zooplankton phenology. The development of the large anoxic zone in Lajoie Lake directly reduces habitat for fish through a DO-temperature squeeze. In this habitat squeeze, suitable fish habitat is restricted to a narrow band of the mixolimnion as monolimnetic waters are too oxygen poor and the top of the mixolimnion exceeds long-term thermal tolerances of cold-water fishes (North et al. 2014; Kerker 2020). Loss of habitat thereby decreases the carrying capacity of the lake (McNaughton & Lee 2010). In Lajoie Lake, this results in approximately 7 m of the water column in the summer months being suitable to the cold-water fish present. The large anoxic zone further impacts food web interactions by altering zooplankton dynamics, particularly of important food sources such as *Daphnia. Daphnia* species are critical prey for higher trophic levels and are diel vertical migrators: they migrate to deeper water during the day to avoid predation (Lampert 1989). However, in Third Sister Lake (recently transitioned to meromixis due to salt inputs) *Daphnia* numbers have drastically declined due to their inability to enter anoxic waters and avoid predation (Judd et al. 2005). Third Sister Lake also experienced a dramatic change in the benthic invertebrate community (Bridgeman et al. 2000). Similar conditions exist in Lajoie Lake to lead to a decline in *Daphnia* and benthic invertebrates, further altering food web dynamics and impacting native fauna.

5.1.1. Purple sulphur bacteria

Purple sulphur bacteria (PSB) found in Lajoie Lake are a unique component of meromictic lakes and add a novel primary production pathway to the ecosystem. PSB reside below the chemocline in anaerobic water, but still within the photic zone, and use sulphide as an electron donor for photosynthesis (Camacho 2009). The density of biomass produced by PSB can be immense. For example, as many as 4 x 10^8 cells/ml has been documented in Mahoney Lake (Overmann et al. 1991). Unfortunately, most research focuses on the unique physiological properties of the bacteria, and much is still unknown about how they influence ecosystems (Zadereev et al. 2017). For example, although PSB can be a significant carbon source (Overmann et al. 1994; Camacho et al. 2001), their contribution to lake productivity can vary widely with light availability

(Camacho & Vicente 1998; Camacho et al. 2000) and it is unclear how much of that carbon is available to higher trophic levels (Zadereev et al. 2017).

The anaerobic and sulphide rich environments PSB require naturally exclude predation from common lake zooplankton, such as copepods and cladocerans. However, laboratory studies have demonstrated that some zooplankton can feed upon PSB (Gophen 1977; Temerova et al. 2002) and copepods have been observed with PSB in hypoxic conditions (Overmann et al. 1999). Nevertheless, the adverse conditions required to consume PSB likely make the trade-off unfavourable, even if the food is abundant. However, when PSB are subject to turbulent mixing at the chemocline, they can become entrained within the mixolimnion (Overmann et al. 1996; Camacho et al. 2000). They can then be consumed by typical lake zooplankton, thus coupling the nutrient cycles of the monimolimnion and mixolimnion (Overmann 1997). While the degree to which this contributes to mixolimnion productivity is uncertain (Overmann et al. 1994; Camacho et al. 2001), PSB provide an additional pathway for nutrients to be recycled up the water column and is furthering the impact of meromixis on the ecology of Lajoie Lake.

5.2. Limitations and conclusion

The scope of this study precluded investigating watershed alterations that could be affecting Lajoie Lake. Several factors at the watershed level could be increasing nutrient loading from the terrestrial environment into Lajoie Lake and contributing to its present condition. For example, mountain pine beetle (*Dendroctonus ponderosae*) infestations are known to increase the leaching of nutrients into surrounding waterways (Clow et al. 2011; Mikkelson et al. 2013). Additionally, the outlet of Lajoie Lake flows through two culverts and residents report frequent flooding of Lajoie Lake's riparian zone as a direct result of culvert damming. Flooding may add organic material to the water and could be a compounding casual factor of the lake's water quality degradation. This study lacked funds to conduct water chemistry analysis of inlet streams and of the lake. I recommend that future studies prioritize investigating watershed effects on water chemistry, and that lake water chemistry be tested annually as part of a monitoring program. Determining lake water chemistry will fill in the missing link between meromixis and water quality degradation that is assumed by this study, but not proven.

This investigation is further limited by its timeframe. Due to logistical and financial constraints, I only collected one summer and autumn of high-resolution data. Therefore, I relied upon intermittently collected historical data, anecdotal observation, and scientific literature to conceptualize the past condition of the lake. This naturally makes the historical condition uncertain, and it remains plausible that the lake has been meromictic in the past and has transitioned back and forth. However, there is no doubt that Lajoie Lake is currently meromictic. Additionally, climate change being the trigger for meromixis is difficult to prove without long-term data or paleo analysis. A sediment coring investigation could resolve the uncertainties described. However, even if a sediment core analysis is conducted, these have not always succeeded in identifying when and why meromixis developed (Hakala et al. 2004). Nevertheless, with all the lines of evidence presented, and the overwhelming literature demonstrating the impacts of climate change on mixing regimes, I contend that Lajoie Lake's condition has developed due to climate change synergistically acting on its topographically shielded location that is predisposed to reduced spring and autumn circulation.

Fully understanding the ecological and water quality impacts meromixis has had on Lajoie Lake would require rigorous study that is beyond the scope of this project. However, from observations and literature review it is clear that meromixis has altered the historical biological composition of Lajoie Lake and established a new ecological stable state. This has implications for the entire field of limnology. While it is understood that climate change continues to affect stratification and mixing regimes, consensus predicts that dimictic lakes will become polymictic or monomictic (Woolway & Merchant 2019; Jane et al. 2021). While other lakes are meromictic due to topographic shielding and endogenic formation (e.g., Halsey 1968), to the best of my knowledge, Lajoie Lake is the only lake globally that has become meromictic through climatic shifts in stratification phenology. Lake Vähä-Pitkusta in Finland is hypothesized to have transitioned to meromixis by a historical climate shift, but this is the only example, and the role of climate remains uncertain (Hakala et al. 2004). Lajoie Lake is small and not well studied, like most lakes globally. Therefore, it is highly probable that Lajoie Lake is not unique; many other lakes could be currently at risk of meromixis, and some may have transitioned already. This possibility may be localized to topographically shielded montane lakes, but it still represents an additional threat to water quality, local ecosystems, and biodiversity that should be treated with great concern.

6. Restoration

The degradation of Lajoie Lake's water quality is reinforced by the positive feedback loops of chemocline strengthening and internal P loading. Furthermore, it is unreasonable to expect that the novel forcing that induced meromixis – climate change – to abate. Conversely, climatic trends are only going to continue to reinforce meromixis in at-risk lakes. A recent report on climate change in the Bridge River valley projected the effects of representative concentration pathways (RCP) 4.5 and 8.5 (a measure of global warming in additional watts of energy added per square meter of Earth surface) on the watershed's temperature (Jost et al. 2017). The report projects the region's annual temperature maximums to increase between and 1.7 °C and 4.0 °C in the 2050s (2041-2070) based on RCP 4.5 and 8.5, respectively. Annual temperature minimums for the 2050s are projected to be slightly higher, increasing between 2.3 °C and 4.5 °C dependent on RCP outcome. Therefore, passive restoration is not a viable solution as the changes seen in Lajoie Lake will only be further reinforced by inaction. Intervention is required to restore Lajoie Lake's water quality.

The root of Lajoie Lake's water quality degradation is a lack of wind energy to induce natural mixing in the spring and autumn. Therefore, restoration will aim to supplement this energy and mimic natural processes by artificially circulating the lake. Induced mixing will supply DO to the sediment-water interface and prevent the development of anaerobic conditions, reduce redox-mediated internal P loading, and ultimately improve water quality (Ashley & Nordin 1999; Alhamarna & Tandyrak 2021). To cease the redox-mediated reactions, a minimum of 5 mg/L of DO must be maintained at the sediment-water interface (Gibbs & Howard-Williams 2018). However, cold water fishes cannot withstand chronic exposure to DO concentrations below 6 mg/L (Davis 1975). Therefore, to restore historical water quality and abiotic ecological conditions of Lajoie Lake, hypolimnetic DO must be restored to at least 6 mg/L.

Fortunately, methods of artificial destratification have been refined over decades of implementation in lakes globally (Gibbs & Howard-Williams 2018). Corbett Lake in British Columbia is a pioneering example of artificial circulation and an excellent analogue to Lajoie Lake. Corbett Lake was similarly found to be meromictic due to topographic shielding restricting spring and autumn circulation (Halsey 1968). An artificial destratification system was experimentally installed and only operated for about 4 weeks in autumn. DO levels remained high throughout the subsequent winter and summer stratification periods. Artificial destratification is proven to increase DO at the sediment-water interface, reduce internal P loading, and improve water quality (Gibbs & Howard-Williams 2018).

6.1. Restoration goals and objectives

Goal 1: Restore holomictic dimixis in Lajoie Lake by completely circulating the water column in the spring and autumn.

Objective 1.1: Achieve isothermal conditions after 8 weeks of destratification.

Objective 1.2: Achieve uniform specific conductance in the water column after 8 weeks of destratification.

Goal 2: Restore Lajoie Lake water quality to historical conditions by ceasing internal nutrient regeneration.

Objective 2.1: Maintain DO concentration above 6 mg/L throughout the water column annually.

6.2. Artificial destratification design

There are many techniques used to increase hypolimnetic DO (Ashley & Nordin 1999), but the simplest and most applicable is the bubble-plume diffuser (Halsey 1968; Gibbs & Howard-Williams 2018). These systems utilize compressed air that is piped to the deepest point in the lake and released through a diffuser. The resulting bubble-plume creates an upward current that entrains and mixes water from all depths as it rises (Schladow 1993). When the plume reaches the surface, the rising water is forced laterally, exposing the DO poor water to the atmosphere, and rapidly oxygenating it. Since the transported water remains denser than the surface layer, it will sink to its neutral buoyancy point. If correctly sized, the gyre currents generated by the bubble-plume eventually mixes and oxygenates the entire lake volume.

6.2.1. Compressor selection and sizing

A synopsis of artificial destratification systems determined that successful systems typically delivered at least 20 standard cubic feet per minute (SCFM) of air per million square feet of lake area and 1 SCFM of air per million cubic feet of lake volume (Lorenzen & Fast 1977). Based on a surface area of 4,488,546 ft^2 and a volume of 187,942,821 ft^3, Lajoie Lake requires between 89.9 and 187.9 SCFM of air to artificially circulate. Using the mean of these two values as a target suggests that Lajoie Lake would require 138.9 SCFM of air for successful destratification.

All destratification systems are limited by the available power supply. Many power sources have been experimented with, but wired electrical power is the only source that supplies sustainable, consistent, and sufficient energy for running compressors (Ashley & Nordin 1999). Therefore, the power of the system for Lajoie Lake is limited by the electrical supply available: 230 V single-phase power. The maximum compressor size possible on this power supply is two 5.6 kW/7.5 hp compressors (11.2 kW/15 hp total). One 5.6 kW rotary vane compressor moves 30 SCFM; therefore, the maximum capacity for artificial destratification on Lajoie Lake is 60 SCFM, 78.9 less than 138.9 SCFM. Taking the lower estimate of 89.9 SCFM still leaves the system underpowered by 29.8 SCFM. Based on this calculation, artificial circulation will not succeed.

However, this calculation is for a system that will succeed regardless of lake conditions, such as its stratification strength and morphometry. Lorenzen and Fast (1977) also provide an equation based on theoretical and experimental testing by Kobus (1968) that calculates the flow of water entrained by a rising bubble plume. It is calculated using equation 4.

$$Q_w(x) = 35.6C(x + 0.8)\sqrt{\frac{-V_0 \ln\left(1 - \frac{x}{h + 10.3}\right)}{u_b}} \qquad (4)$$

$Q_w(x) =$ water flow at depth x (m^3/s)

$x =$ height above the diffuser (m)

$C = 2V_0 + 0.05$

$V_0 =$ air flow (m^3/s)

$$h = \text{the depth of the diffuser (m)}$$

$$u_b = 25V_0 + 0.7\ \text{m/s}$$

If the entire lake volume can be circulated in a reasonable time frame based this equation, then the destratification will likely succeed at oxygenating the lake. Given a diffuser depth of 20 m and an air flow of 0.0283 m^3/s (60 SCFM of air), the water flow at the lake surface would be 11.6 m^3/s. At this rate it would take approximately 5.3 days to circulate Lajoie Lake's volume of 5,321,943 m^3. Therefore, 8 weeks of aeration should be capable of oxygenating the entire lake volume.

Furthermore, the success of destratification depends on many factors, including the shape of the lake basin, the depth of the diffuser, and the thermal properties of the water (Gibbs & Howard-Williams 2018). The efficiency of destratification increases as the water approaches isothermal conditions (Gibbs & Howard-Williams 2018) and with increasing diffuser depth (Cooke et al. 2005). Destratification in Lajoie Lake will occur at near isothermal conditions in the spring and autumn and the diffuser will be placed relatively deep at around 20 m. Furthermore, while wind energy is insufficient to overturn the lake individually, it will still provide additional energy in tandem with the compressors. Finally, over 30 years of professional experience with a similarly underpowered scenario resulted in successful destratification at 1/2 to 1/3 the recommended compressor output (pers. comm., Ken Ashley, BCIT Rivers Institute). In conclusion, I contend that an 11.2 kW artificial destratification system in Lajoie Lake will be sufficiently powered and succeed at fully circulating and oxygenating the water column.

6.2.2. Diffuser placement

Diffuser placement is paramount to successful and efficient destratification. To maximize the efficiency of mixing, the diffuser should be placed in the deepest location of the lake (Fig. 18) (Lorenzen & Fast 1977). Additionally, the diffuser should be installed as deep as possible to fully mix the water column and further improve efficiency (Cooke et al. 2005). However, it is important not to place the diffuser directly on the bottom as this disturbs bottom sediment and will greatly increase the oxygen demand (Beutel 2003). This occurred during experimental destratification of meromictic Yellow Lake and the increased oxygen demand resulted in a fish kill (Halsey & Macdonald 1971). To mitigate this risk in Lajoie Lake, the diffuser pores should be oriented up and the diffuser should be located about 3 m off the bottom sediment at minimum.

Figure 18. **Approximate location of the aeration diffuser and the monitoring station to be used while destratification is in progress.**

6.3 Timing and duration

Artificial destratification is commonly used in British Columbia to prevent winterkills of fish (Ashley et al. 1992). A winterkill event occurs when DO demand in ice covered eutrophic lakes overcomes the supply from autumn turnover. The result is the suffocation of fish as whole lake DO concentrations decline below acute tolerance limits. While much expertise on artificial destratification comes from these systems (Ashley & Nordin 1999), they were not designed to mimic natural processes but rather promote artificial fisheries. As the goal is the restoration of Lajoie Lake, we will aim to artificially recover the lost natural processes: spring and autumn mixing. Therefore, the artificial destratification system will only be activated after ice-off and before ice-on. These two mixing periods should provide sufficient DO for both stratification periods as the DO demand in oligotrophic lakes is less than that of eutrophic lakes that exhibit winterkill (Ashley et al. 1992). For example, successful reoxygenation of monimolimnetic waters occurred in less than six weeks of autumn destratification in both Corbett Lake (Halsey 1968) and Yellow Lake (Halsey & Macdonald 1971).

To ensure that the underpowered destratification system in Lajoie Lake can supply sufficient DO, artificial circulation will occur in both the spring and autumn. To maximize the system efficiency, circulation will occur as much in isothermal conditions as possible. As such, ice-off and ice-on dates from the 2022 season will inform the timing of circulation (Table 3). Spring circulation begins underneath ice cover once open water is present along the shores (Kirillin et al. 2012). To maximize the time spent mixing under ideal conditions, artificial circulation should begin 24 March, about two weeks before the lake begins naturally circulating 8 April. The compressors will run for about 8 weeks until 19 May. However, this timeline will depend on adaptive management described in section 6.4.1. Autumn destratification will similarly maximize the time operating in ideal conditions. Therefore, the 8-week autumn window will occur from approximately 15 October to 15 December. However, these operation windows will depend on yearly conditions and adaptive management. A key limiting factor of autumn destratification is the legal complications associated with the creation of a hole in the ice. Section 263 of the Canadian Criminal Code states that any holes created in ice must be adequately signed and guarded to prevent injury (Criminal Code 1985). Therefore, destratification during complete ice-cover should be avoided due the added cost and difficulty of managing the hole formed by the bubble-plume.

Table 3. Progression of ice cover on Lajoie Lake in 2022.

Date	Ice status
Open Water	8 April
Ice movement	17 April
Ice free	23 April
First shore ice	13 November
First complete ice cover	2 December
Permanent ice cover	9 December

6.4 Operational refinement and monitoring

6.4.1 Adaptive management during destratification

Operation of the destratification system for 8 weeks bi-annually is a starting point only. Precise operation will depend on continuous monitoring and refinement of the operational periods. Monitoring during destratification should occur in the south basin as this will be more representative of whole lake mixing (Fig. 18). During destratification, temperature and DO profiles should be collected weekly at minimum. This is to monitor bottom-layer warming during spring destratification and water column deoxygenation during both destratification windows. Warming the bottom layer should be avoided as this will increase the oxygen demand in the sediment and degrade the cold water refugia. Mixing of the water column during artificial destratification can result in initial epilimnetic deoxygenation (Halsey & Macdonald 1971). Therefore, DO should be closely monitored both for success of aeration, but also to keep minimum DO levels above 6 mg/L – the chronic tolerance level of cold-water fishes (Davis 1975). I recommend the following operating procedures adapted from Gibbs & Howard-Williams (2018).

Spring destratification procedures

1) Surface water is < 1 °C warmer than bottom water, surface layer DO is > 8 mg/L, and bottom layer DO is < 6 mg/L: continue destratification and maintain monitoring frequency.

2) Surface water is 1-2 °C warmer than bottom water, surface layer DO is > 8 mg/L, and bottom layer DO is < 6 mg/L: continue destratification and increase monitoring frequency to twice weekly.

3) Surface water is > 2 °C warmer than bottom water, surface layer DO is > 8 mg/L, and bottom layer is < 6 mg/L: discontinue destratification as system cannot destratify the water column and bottom heating will occur. Consider earlier operation the following spring.

4) Surface water is < 2 °C warmer than bottom water, surface layer DO is 6-8 mg/L, and bottom layer DO is < 6 mg/L: continue destratification but increase monitoring frequency to twice weekly as risk to fish is elevated.

5) Surface water is < 2 °C warmer than bottom water, surface layer DO is < 6 mg/L, and bottom layer DO is < 6 mg/L: pause destratification as fish kill risk is elevated.

6) Surface water is 1-2 °C warmer than bottom water, surface layer DO is > 8 mg/L, and bottom layer DO is > 6 mg/L: discontinue destratification as DO is sufficient and unnecessary bottom layer heating will occur if aeration is continued.

7) Surface water is < 1 °C warmer than bottom layer and DO is uniform in the water column between 6-8 mg/L: continue destratification as circulation is successful but DO can increase.

8) Surface water is < 1 °C warmer than bottom layer and DO is uniform in the water column at > 8 mg/L: discontinue destratification as circulation and oxygenation is successful.

Autumn destratification procedures

Bottom layer heating during autumn circulation is not a concern as the cold air temperatures will replenish cool water prior to freeze-over (Kirillin et al. 2012). As such, the following procedures should be followed during autumn destratification.

1) Bottom layer DO is < surface layer DO, and surface DO is > 8 mg/L: continue destratification.

2) Bottom layer DO is < surface layer DO, and surface DO is 6-8 mg/L: continue destratification but increase monitoring frequency to twice weekly as risk to fish is elevated.

3) Bottom layer DO is < surface layer DO, and surface DO is < 6 mg/L: pause destratification as fish kill risk is elevated.

4) DO is uniform in the water column and 6-8 mg/L: circulation is successful but continue destratification to increase DO.

5) DO is uniform in the water column and > 8 mg/L: discontinue destratification as circulation is successful and water column is oxygenated.

6.4.2. Ongoing monitoring, annual management, and long-term conditions

Continuous monitoring should be conducted during the summer and winter stratification periods to evaluate the success of aeration. If hypolimnetic DO declines below 6 mg/L during these periods, future destratification should be extended to increase DO levels. Monitoring during the ice-off season should follow the protocols currently in use by the BC Lake Stewardship Society (BC Lake Stewardship Society 2008). This involves bi-weekly profiles of DO and temperature, in addition to Secchi depth measurement. Maintaining historical methods will enable comparison to conditions prior to the implementation of the destratification system. Additionally, I recommend descriptive documentation of lake water quality condition to continue the oral history of the lake already established by the long-time residents.

Furthermore, I suggest adding to the established monitoring plan by incorporating winter measurements. Conducting sampling of DO and temperature profiles under the ice-cover of Lajoie Lake will reveal the oxygen demand of the lake during the winter and determine the success of autumn destratification. I recommend monthly profiling of the lake, dependent on ice safety conditions. If DO concentrations decline after autumn aeration, then the duration of circulation should be extended. If limited DO consumption occurs over the winter, it may indicate that spring circulation is unnecessary. Many lakes have limited spring circulation due to the delay of ice melt relative to the increases in air temperature (Boehrer et al. 2017). In this case, autumnal circulation provides sufficient DO for the entire year. Corbett Lake (Halsey 1968) and Yellow Lake (Halsey & Macdonald 1971) are examples of this scenario. Finally, I recommend annual testing of epilimnetic and hypolimnetic water chemistry to assess the effect of aeration on lake nutrient concentrations.

Long-term decadal management of Lajoie Lake is much more difficult to forecast. Artificial destratification will improve the water quality of Lajoie Lake in the short-term and will hopefully provide a useful template and learning opportunity for other lakes that become similarly impacted by climate change. However, if climate change is not curtailed, it is difficult to predict how Lajoie Lake will be affected in the future. I find it likely that the influence of climatic warming may eventually overtake the power of the destratification system, and the maintenance of Lajoie Lake's water quality and mitigation of climate change impacts might become impossible. In the long-term, the only sustainable way to address the degradation of Lajoie Lake, and lakes similarly afflicted, is to mitigate climate change itself.

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Appendix A. Bathymetric map

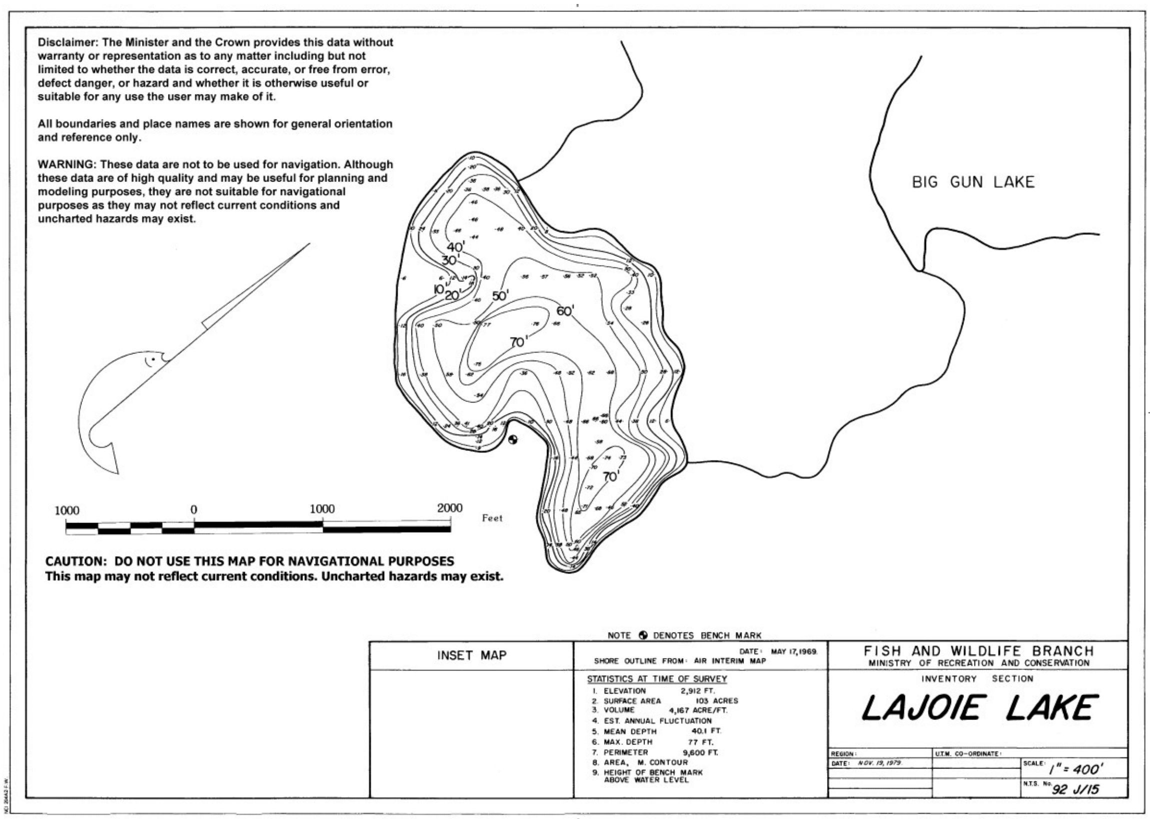

Figure A1. **Bathymetric map of Lajoie Lake (British Columbia Ministry of Environment 1979)**

Appendix B. Sampling Schedule

Table 1B. Sampling schedule during the 2022 ice-off season.

Ice-off Date: 23-Apr-22		Install/Remove Weather Station	Install/Remove Thermistor String	Measure DO and Temperature Profiles	Measure Specific Conductance Profile	Measure Secchi Depth	Measure Turbidity
Days From Ice-off	Date						
8	01-May-22						
25	18-May-22						
40	02-Jun-22						
52	14-Jun-22						
66	28-Jun-22						
94	26-Jul-22						
124	25-Aug-22						
159	29-Sep-22						
191	31-Oct-22						
209	18-Nov-22						

Appendix C. Water Clarity

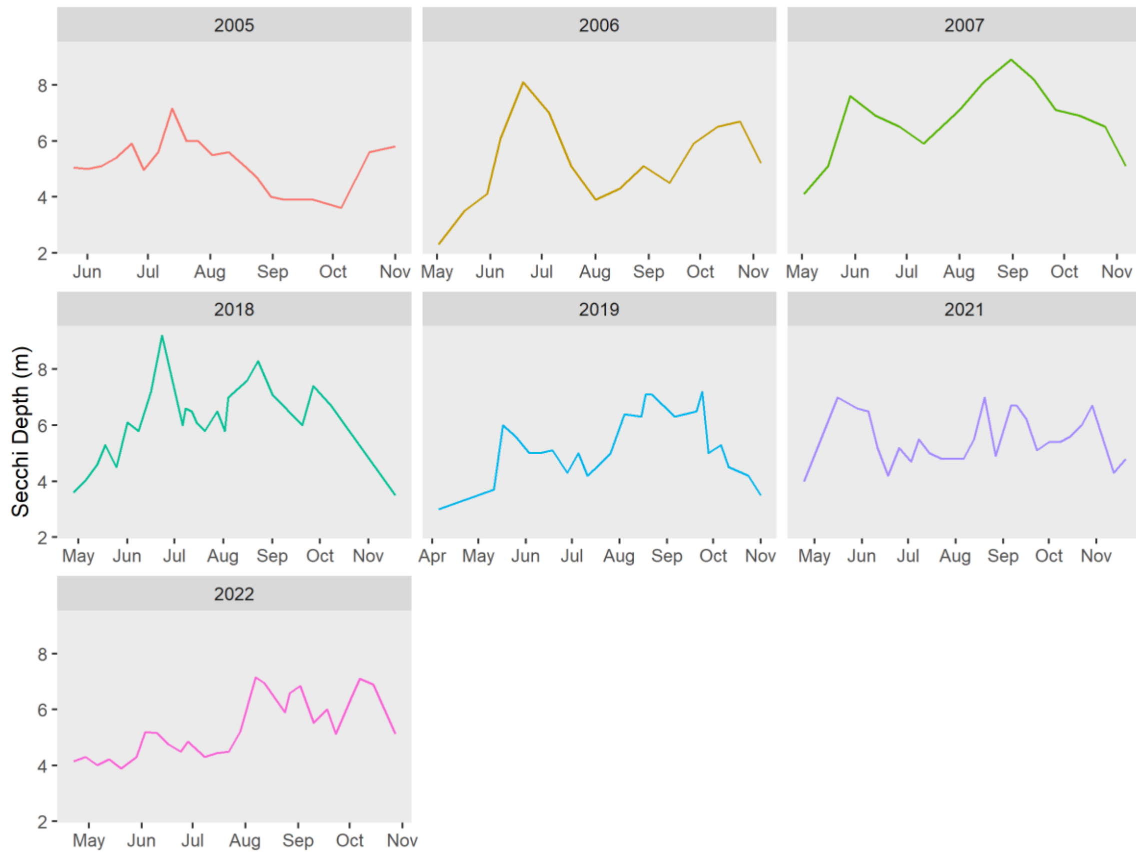

Figure 1C. **Trends in Secchi depth (m) from 2005 to 2022, collected by the British Columbia Lake Stewardship Society.**

Table 1C. **Secchi depth (m) and turbidity (NTU) recorded during the 2022 ice-off season for this investigation.**

Date	Secchi Depth (m)	Turbidity (NTU)
01-May	2.62	
18-May	4.8	0.27
02-Jun	5	0.13
14-Jun	5.7	
28-Jun	4.5	0.48
26-Jul	5.5	0.14
25-Aug	6.66	
30-Sep	7.24	0.44
31-Oct	7.85	
18-Nov	6.4	

Appendix D. Air Temperature

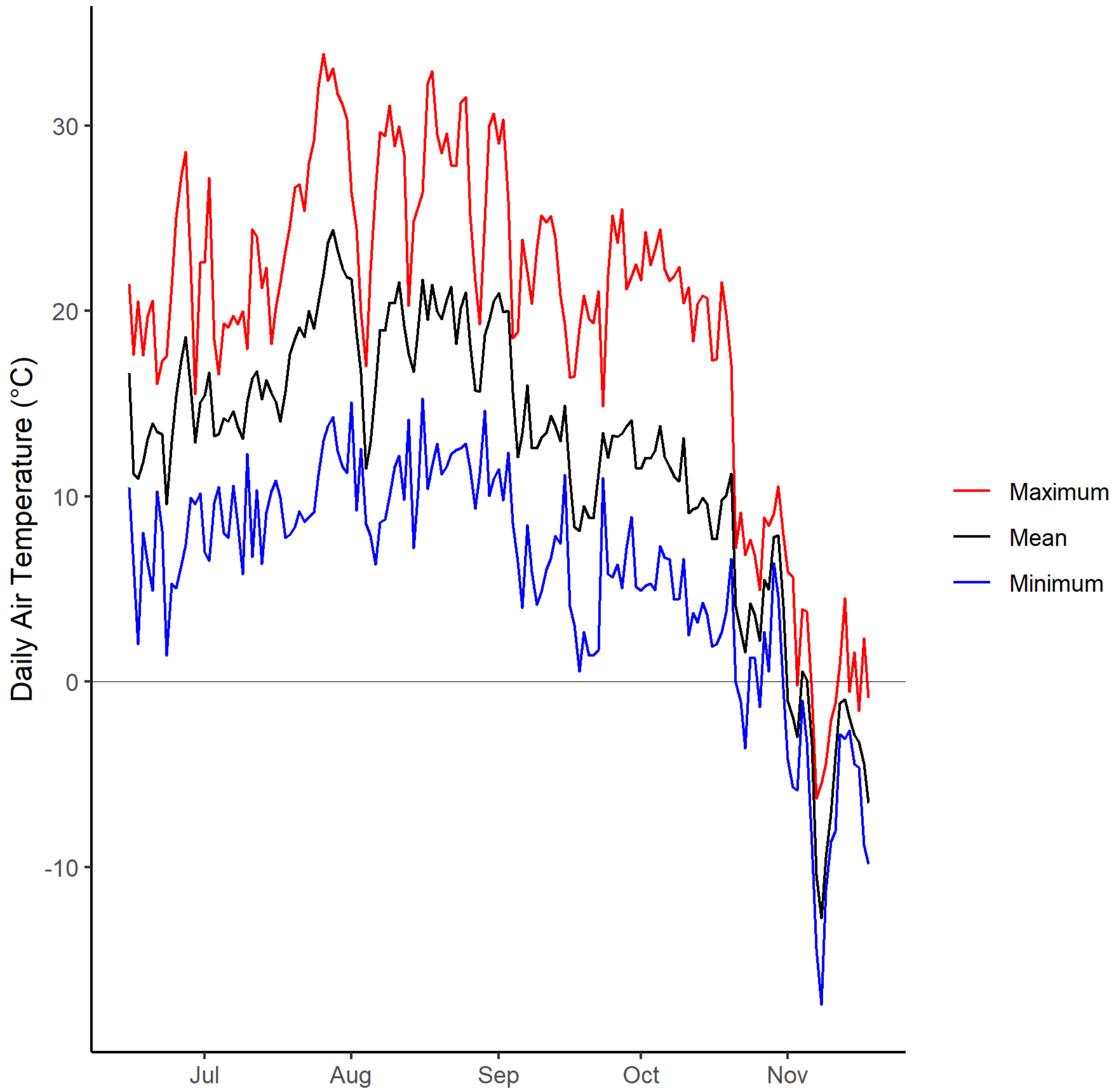

Figure 1D. **Daily air temperature measures of Lajoie Lake from June 14 to November 18, 2022. Data is summarized from current temperature logged every 10 minutes during this period.**

Appendix E. Historical Profiles

Table 1E. Depth profile of Lajoie Lake's temperature and dissolved oxygen from 15 May 1969 (Harding & Offin 1969).

Depth (ft)	Temperature (°F)	Dissolved Oxygen (mg/L)
1	56	6
10	55	7
12	53	-
13	52	-
14	50	-
15	50	-
16	49	7
19	47	-
23	45	-
24	44	-
29	42	-
34	41	-
50	-	10
52	40	-
65	40	-
72	40	-

Table 2E. Depth profile of Lajoie Lake's temperature and dissolved oxygen from 11 June 1980 (Caverly 1980).

Depth (m)	Temperature (°C)	Dissolved Oxygen (mg/L)
0	14	8.4
1	13	7.5
2	13	4.7
3	11	3.7
4	10	3.0
5	8	2.7
6	6	2.6
7	5	2.5
8	4	2.6
9	4	2.7
10	3	2.7
11	3	2.8
12	3	2.8
13	3	2.8
14	4	2.7
15	4	2.6