Title: Four meromictic (?) lakes in Itasca State Park, Minnesota, U.S.A.

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Abstract

Four adjacent lakes (Arco, Budd, Deming, and Josephine) within Itasca State Park in Minnesota, USA are reported to be meromictic in the scientific literature. However, seasonally persistent chemoclines have never been documented. We collected seasonal profiles of temperature and specific conductance and placed temperature sensor chains in two lakes for ~ 1 year to explore whether these lakes remain stratified through seasonal mixing events, and what factors contribute to their stability. The results indicate that all lakes are predominantly thermally stratified and are prone to mixing in isothermal periods during spring and fall. Despite brief, semi-annual erosion of thermal stratification, Deming Lake showed no signs of complete mixing from 2006 to 2009 and 2019-2022. Geochemical data indicate that water in Budd Lake, the most dilute lake, is predominantly sourced from precipitation. The water in the other three lakes is calcium-magnesium bicarbonate type, reflecting a source of water that has interacted with the landscape. $\delta^{18}O_{H2O}$ and $\delta^{2}H_{H2O}$ measurements indicate the lakes are supplied by precipitation modified by

evaporation. The water residence time in meromictic Deming Lake is short (100 days), yet it maintains a large reservoir of dissolved iron. Josephine, Arco, and Deming lakes sit in a valley with likely permeable sediments and may be hydrologically connected through wetlands, and recharged with shallow groundwater, as no streams are present. All four lakes develop subsurface chlorophyll maxima layers during the summer. All lakes also develop subsurface oxygen maxima that may results from oxygen trapping in the spring by rapidly developed thermoclines.

Introduction

Meromictic lakes, which do not mix seasonally, maintain anoxic bottom waters that minimize sediment resuspension and bioturbation and permit the development of laminated or varved sediments (Anderson et al. 1985; Anderson and Dean 1988). Such sediments can record climatic transitions, vegetation changes, changes in sediment transport, and atmospheric deposition patterns (O'Sullivan 1983). Laminated sediments are also useful for studying the formation, deposition, and diagenetic transformation of chemically precipitated minerals (Wittkop et al. 2020; Ledesma et al. 2022). Such sediments are useful to interpret the origin of minerals in sediments deposited from past stratified marine waters when such conditions no longer exist(Degens and Stoffers 1976; Swanner et al. 2020). Meromictic lakes are present on all continents but are thought to be rare (Walker and Likens 1975; Stewart et al. 2009; Hall and Northcote 2012).

Lakes can develop meromixis when surface wind action does not mix the epilimnion, the upper layer of the lake, with the monimolimnion, the deepest layer of the lake. Meromictic lakes are characterized by a sharp increase in electrical conductivity at a chemocline separating a cold and/or dense monimolimnion from the epilimnion (Boehrer and Schultze 2008). The epilimnion is in contact with the atmosphere, while the monimolimnion is anoxic. This results in changing sedimentation patterns compared to lakes that mix regularly. A sediment indicator of an anoxic monimolimnion typical of low sulfur meromictic lakes is enhanced burial of oxygen-sensitive mineral forming elements, particularly iron and manganese (Dean and Schwalb 2002; Wittkop et al. 2014).

Lake morphometry is a key factor in the development of meromixis. Lakes that are relatively deep compared to their surface area, which determines the fetch upon which wind can act, are less likely to overturn (Wetzel 2001). The potential for water column stratification is reflected by relative depth (Z_r), which is the ratio of the maximum lake depth (Z_m) to the diameter of a circle of area equal to that of the lake (A^0), expressed as a percentage.

$$Z_r\ (\%) = \frac{Z_m}{2}\sqrt{\frac{\pi}{A_0}} \times 100 \qquad (1)$$

Most temperate zone lakes prone to meromixis have relative depths exceeding 4% and A^0 of less than 0.5 km^2 (Swanner et al. 2020). Meromixis can also result from increased chemical constituents that enrich the water density of monimolimnion, such as from runoff, groundwater inputs, and remineralization processes associated with organic carbon loading (Hakala 2004; Schultze et al. 2017). The identity of the substances causing increased density varies depending on the catchment characteristics but can include dissolved iron and manganese, as well as dissolved inorganic carbon (Kjensmo 1967; Hongve 2002).

Gradients of dissolved oxygen and inorganic nutrients are mediated by primary productivity and uptake in the epilimnion and sinking and decomposition of biomass in the monimolimnion (Camacho 2006). Stratification limits the return of nutrients to the epilimnion. A subsurface chlorophyll maximum layer (SCML) often develops within the metalimnion, the middle seasonally mixed layer of meromictic lakes (Baker and Brook 1971; Camacho 2006).

Stable stratification, the availability of both light and nutrients, and zooplankton grazing drive the formation and location of the SCML in meromictic lakes (Klausmeier and Litchman 2001; Pilati and Wurtsbaugh 2003). Primary productivity is often highest within the SCML (Camacho 2006).

Four lakes in Itasca State Park, Minnesota, USA - Arco, Budd, Deming, and Josephine (Figure 1) - have been described as meromictic in the scientific literature since the 1960s (Baker and Brook 1971; Anderson et al. 1985; Stewart et al. 2009). However, there has never been physical and chemical data from all lakes during all seasons - especially spring and fall when mixing would be expected - to document through the maintenance of a chemocline that they are meromictic. The goals of this study are to 1) determine whether these four lakes are meromictic, 2) investigate the water type, sources, and reasons for meromixis, and 3) describe the unique biological features of these lakes. To achieve these goals, we conducted fieldwork from 2006-2009 and 2019-2022, and integrated data from University of Minnesota students working at the Itasca Biological Station and Laboratories since the 1950s. We hope that this description of the lakes will spur new investigations that utilize their unique geomorphological and biogeochemical features.

Methods

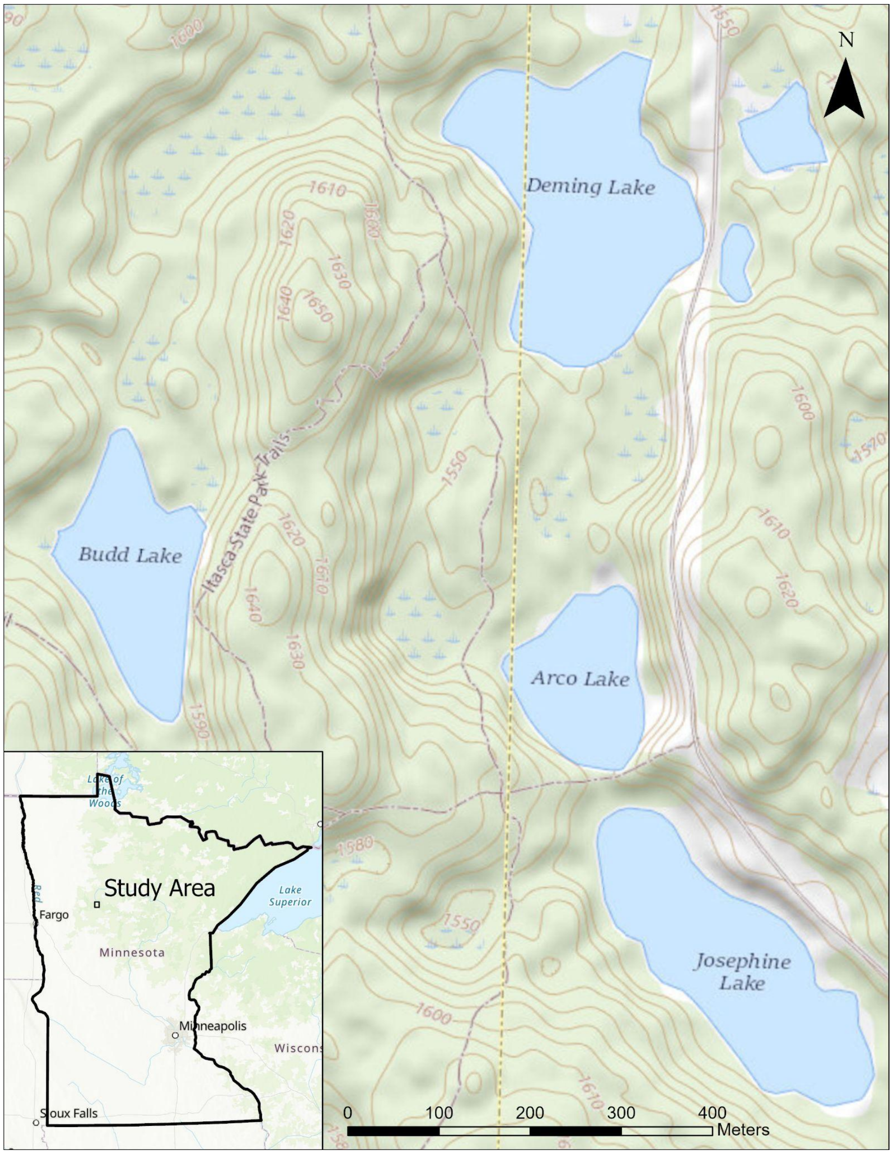


Figure 1: Map of the four study lakes within Itasca State Park, Minnesota.

Formation of the four study lakes occurred during the late-Wisconsin glaciation ~12,000 years ago (marine isotope stage 2; Jennings and Johnson 2011). They occupy a tunnel valley that was formed beneath the Wadena lobe of the Laurentide Ice Sheet. Following glacial retreat, the melting of stagnant ice blocks within the tunnel valley left depressions in the landscape now occupied by lakes and wetlands (Wright Jr. 1993).

Today, the four lakes investigated in this study sit in the HUC-12 watershed that sources the headwaters of the Mississippi River (U.S. Geological Survey 2017). Budd (478.6 meters above mean sea level; MAMSL) is the highest elevation, while Arco (465.8 MAMSL) and Josephine (465.4 MAMSL) lie at similar elevations. Deming is the lowest elevation of the lakes (464.8 MAMSL).

Lake depth measurements were collected using a Garmin Striker 4 dual-beam transducer (sonar) attached to a rowboat or canoe. Depth and GPS measurements were taken every six seconds while the boat was in motion. A Garmin GLO 2 GPS receiver and ArcGIS Collector app was used to navigate, track the boat's course, and ensure even coverage. The shoreline of the lakes was obtained by walking along accessible areas of the shore with the Garmin GLO 2 GPS receiver, or from Lidar-derived digital elevation models. Bathymetry rasters (1 m resolution) were generated from the depth measurements in ArcGIS Pro 3.0 using a 3rd-degree Local Polynomial Interpolation. These rasters were used to calculate lake volumes and contour maps. Rasters and volume data have been deposited with the Environmental Data Initiative (Swanner et al. 2022).

Chemical, physical, and biological parameters measured on the four lakes included depth, temperature, specific conductance, salinity, turbidity, pH, oxidation-reduction potential, dissolved oxygen, photosynthetically active radiation, chlorophyll-a, and phycocyanin. Major cations, anions, and isotopes of water ($\delta^{2}H$-H_2O and $\delta^{18}O$-H_2O) were determined on lake water retrieved from different depths within the four lakes. Taxon-specific chlorophyll-a fluorescence was collected with a Fluoroporbe (BBE Moldaenke). The data and description of methods are available in the Environmental Data Initiative (Swanner et al. 2022).

A string of temperature loggers (HOBO Water Temp Pro v2) placed at different depths were deployed into the deep areas of Deming, Arco, and Budd lakes for one year. A conductance logger (HOBO Conductivity Logger) was added near the bottom of the strings in Arco and Budd after six months. These sensors measured temperature every thirty minutes and specific conductivity every 2 hours. The sensor string was not retrieved from Budd, as it could not be located. Conductance measurements with a Yellow Spring Instruments ProDSS temperature/conductivity sensor on deployment and removal were used to check for drift in the HOBO conductance logger. Hourly wind speed data for the duration of sensor deployment utilized the ITCM5 weather station in Itasca State Park. Data was downloaded from MesoWest (https://mesowest.utah.edu/). Plots and analyses were produced in Python or R Studio (2022.07.2) using the RLakeAnalyzer package v.1.11.4.1 (Winslow et al. 2019).

Major anions (CO_3^{2-}, HCO_3^-, Cl^-, and SO_4^{2-}) and cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) were used to produce a Piper diagram in Geochemist's Workbench 15.0. The concentration of cations and anions was calculated as the percentage of total cations and anions in meq L^{-1}.

The isotopes of water (δ^2H_{H2O} and $\delta^{18}O_{H2O}$) were measured on spring or seep water that had been filtered with 0.45 micron nylon syringe filters and stored at 4 °C with minimal headspace until analysis. Samples were analyzed with a Picarro L1102-i Isotopic Liquid Water Analyzer at the Stable Isotope Laboratory at Iowa State University. The analytical uncertainty and average correction factor for $\delta^{18}O_{H2O}$ are ± 0.05 ‰ and ± 0.30 ‰ for δ^2H_{H2O} relative to V-SMOW.

Samples for microscopy and water color were collected into amber bottles with a Van Dorn sampler from three different depths in each lake, including the SCML, if present, as determined with the YSI ProDSS. Water color was determined on water filtered through a GF-75 (Advantec) glass fiber filter (Cuthbert and del Giorgio 1992). Absorbance was measured at 440 nm and 750 nm. The absorbance at 750 nm was subtracted from the absorbance at 440 nm. The absorption coefficient was calculated with the equation:

$$g\ (m^{-1}) = (2.303 * \text{Absorbance})/(\text{path length}) \quad (2)$$

A conversion was necessary to determine the color of the lake water as seen below.

$$\text{Color (mg Pt } L^{-1}) \ g_{440}\ (m^{-1}) = 18.216*[g_{440}\ (m^{-1})] - 0.209 \quad (3)$$

Water sampled from the SCML was preserved with 1% Lugol's solution upon returning to the lab. Fixed samples were settled in the dark for three to seven days.

Student reports from courses taking place over several decades at the Itasca Biological Station and Laboratories (IBSL) (Knoll and Cotner 2018), formerly the Itasca Biological Station, were acquired from the library at the University of Minnesota, Twin Cities.

Results & Discussion

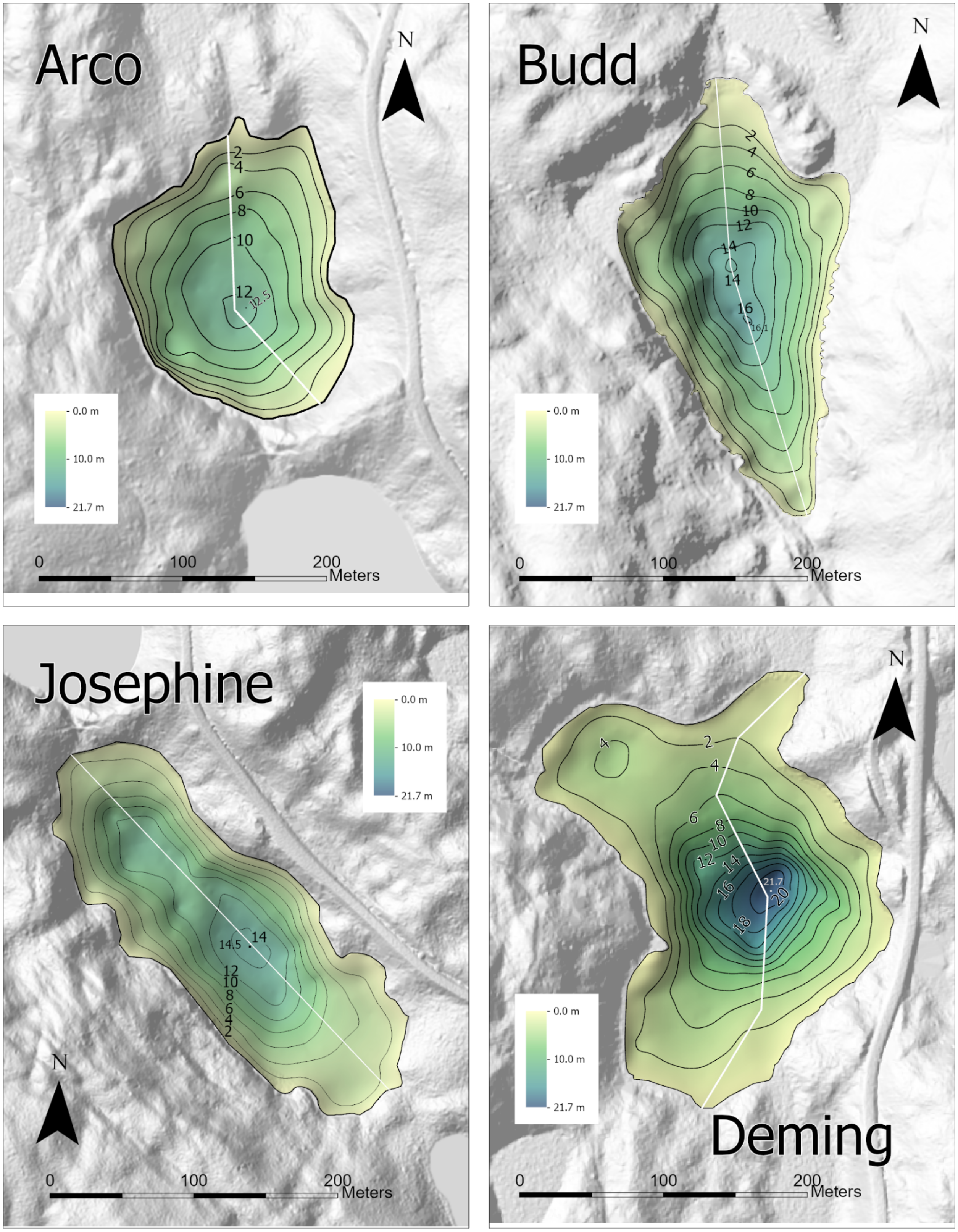
Table 1. Morphometric parameters for the four study lakes.

Lake	Volume (m^3)	Surface Area (m^2)	Maximum Depth (m)	Relative Depth (%)	Fetch Distance (m)	Fetch Heading (degrees)
Arco	142,628.73 m^3	24180 m^2	12.6 m	7.3%	210.4 m	175 deg.
Budd	183,441.22 m^3	28184.5 m^2	16.1 m	8.8%	310.3 m	169 deg.
Deming	242,701.12 m^3	54325 m^2	20.8 m	7.3%	346.7 m	188 deg.
Josephine	315,765.05 m^3	52711 m^2	14.5 m	5.7%	432.4 m	136 deg.

Morphometry and Mixing Status

Deming is the largest and deepest of the four study lakes with a 54,325 m^2 surface area and a maximum depth of 20.8 meters (Table 1). The maximum depth of Deming Lake has previously been reported as 16.5 m (Hooper 1951), 17 m (Baker and Brook 1971), and 17.6 m (Lascu and Plank 2013). Differences in technology and the small surface area (4.3%) with water depths at or below 17 m could account for the variation. Long-term water-level fluctuations may be induced by drought (Lascu et al. 2012). In all lakes, steep-sided deep holes were detected (Figure 2). It is possible that temperature, pressure, and/or salinity gradients present at the tops of these holes could deflect sound beams, causing errors in our depth measurements (Boehrer and Schultze 2008). These factors could have affected all lakes, which were found to be systematically deeper than previously reported.

Josephine has the longest fetch and lowest Z_r of all study lakes. The maximum depth of Josephine Lake (14.8 m) has previously been reported as 10.3 m (Baker and Brook 1971), 12-13 m (Callis et al. 1976), and 13 m (Gage and Gorham 1985). The surface area with depths at or below 13 m in Josephine Lake is 5.1%. There was the greatest variation between the previously reported maximum depth of Budd Lake (10.8 m; Baker and Brook 1971) and ours (16.1 m). Budd Lake has the highest Z_r (8.8%). Arco Lake has the smallest surface area of 24,180 m^2 and a maximum depth of 12.8 m. Arco and Budd Lakes have steep banks along their eastern sides (Figure 1). All lakes exceed a Z_r of 4% and have surface areas of less than 500,000 m^2, typical of meromictic lakes in the temperate zone (Swanner et al. 2020).


Arco
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Budd
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Josephine
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21.7
0.0 m
10.0 m
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Deming
0
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Meters

Figure 2. Bathymetric maps of the study lakes overlain on the digital elevation models. Depth is in meters. The fence diagrams correspond to the cross-sections in Supplementary Figure 1.

Deming Lake has the longest record of seasonal profiles (2006-2009 and 2019-2022), as its sediments have previously been used to investigate Holocene climate variations (Lascu et al. 2012; McLauchlan et al. 2013). A chemocline, or sharp increase in specific conductance, persists in Deming Lake at all sampled times (Figure 3), which is expected for a meromictic lake. The chemocline occurs at 11-13 m (Figure 3). The chemocline was below 10 m in 1989 (Church et al. 1989), and from 11-13 m a decade later (Reiter et al. 1998) based on temperature-compensated conductance measurements from IBSL student reports, indicating that the chemocline has been at a consistent depth for decades. Earlier observations from numerous student reports indicate a much shallower chemocline in Deming Lake, below 5 m (Engstrom et al. 1974; Karli and Keller 1975; Habedank 1990; Bieter et al. 1991; Condon et al. 1996; Nelson et al. 2011). Many of these measurements were made as conductivity without a standardized cell geometry and may or may not have been corrected to a temperature of 25°C, which is necessary for comparing samples across the thermocline. The temperature-compensated and specific cell geometry measurements in our dataset (i.e., specific conductance) likely better capture the variation in dissolved ions comprising the chemocline.

A systematic increase in the magnitude of specific conductance readings below the chemocline was observed from the 2006-2009 to the 2019-2022 datasets (Figure 3). This could either be an artifact of instrumentation and calibration differences between the two datasets or could represent a temporal change in water column properties. The counties encompassing Itasca State Park experienced extreme drought for several months in the spring of 2006 and exceptional drought for a few weeks in the summer of 2021(National Oceanographic and Atmospheric Administration; Supplementary Figures 2 and 3). This could have increased the lake's salinity through increased evaporation (Jellison and Melack 1993). Alternatively, or in addition, the magnitude of water sources of differing salinities may have been altered (Ludlam and Duval 2001). In the second case, a drought would decrease the magnitude of low specific conductance precipitation and increase the proportion of higher specific conductance groundwater to the annual water budget. As Deming Lake does not have a surface inlet, changes in streamflow can be neglected. The period from 2006-2009 was generally dry, and the amount of recharge to the groundwater system may have also decreased over a multi-year period, effectively decreasing groundwater inputs to the lake, and counteracting the effects of evaporation on specific conductance in Deming Lake. In 2019-2022, the exceptional drought was short-lived and specific conductance might better reflect decreases in precipitation than decreases in recharge, resulting in greater specific conductance values. Another possibility is that variations in the amount of in-lake primary productivity could modulate the specific conductance in the monimolimnion (Campbell 1977). Finally, a longer time since a mixing event could also increase the dissolved solute load from 2019-2022 relative to 2006-2009 (Katsev et al. 2010).

A chemocline was present at all time points for Arco Lake between 7-10 m except for May 2022 (Figure 3). It was poorly developed in May 2021, and its deepest occurrence was in January 2021. Arco Lake has a maximum depth of 12.8 m, but no specific conductance data was collected below 12 m as part of the profiles acquired during the study period due to the difficulty of finding the small deep spot (1.7% of surface area). The chemocline is shallowest in mid-summer, consistent with the 7 m chemocline observed in temperature-equilibrated conductivity readings in 1975 and 1976 (Evans and Bjerklie 1975; Barnes et al. 1976), and 2011 (Harren et al. 2011).

Budd Lake had the lowest range of specific conductivity values (23-90 µS cm^{-1}). A weakly demarcated chemocline was observed around 4-5.5 m water depths for May 2021, July 2021, October 2021, and May 2022. The January 2021 profile shows a deeper chemocline (Figure 3).

Specific conductance values were uniform down to 8 m in Josephine Lake during the current study period (Figure 3). A chemocline was only detected below 11 m in May 2022, while depths below 11 m were not assessed on other dates during the study period due to the difficulty of finding the deepest area before mapping in 2022. Autumnal circulation down to 10 m was reported in Josephine Lake in 1975 (Gage and Gorham 1985).

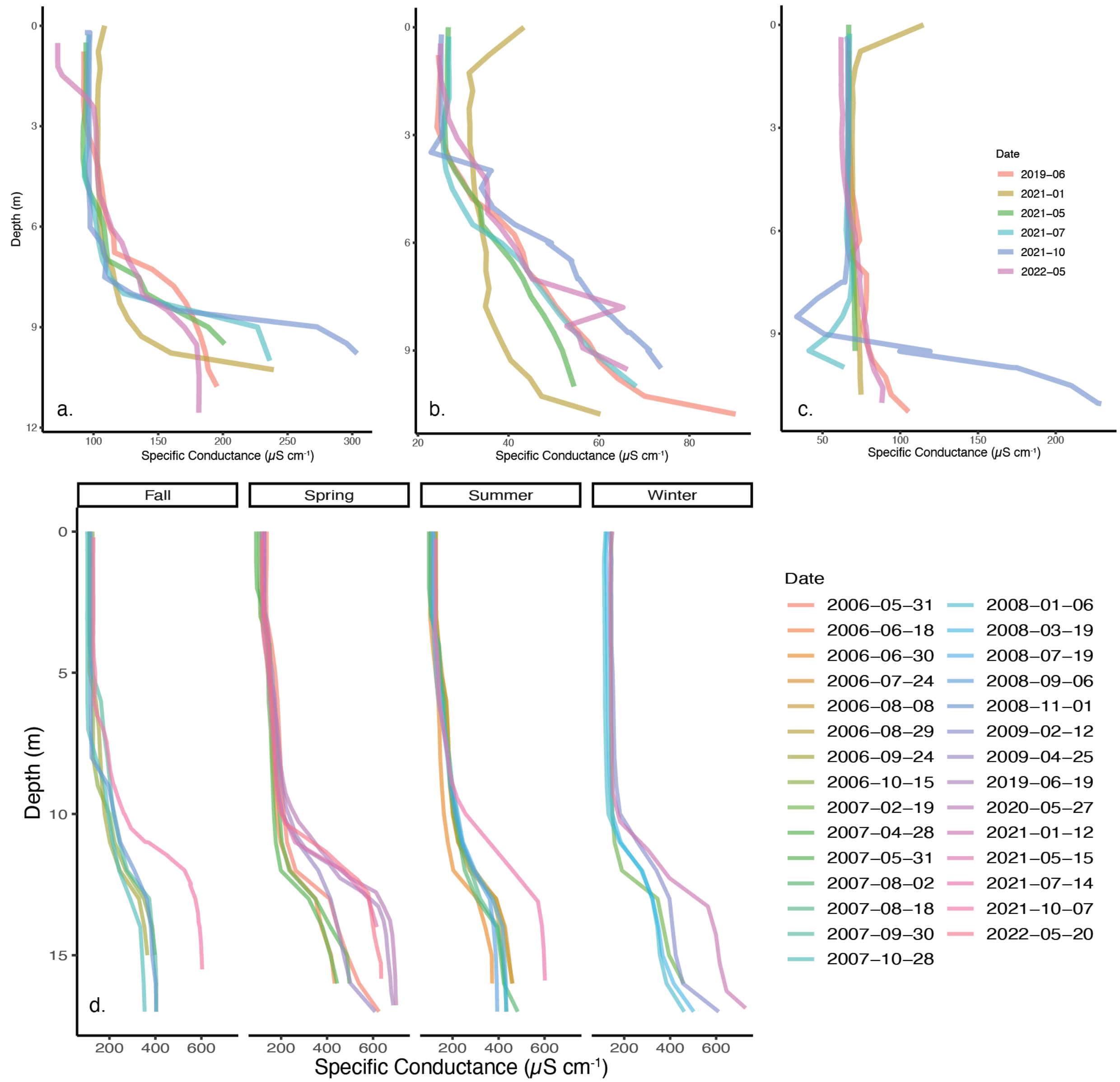

Figure 3. Specific conductance profiles of a) Arco Lake, b) Budd Lake, c) Josephine Lake, and d) Deming Lake. For Deming Lake, seasons were classified according to solstice and equinox dates.

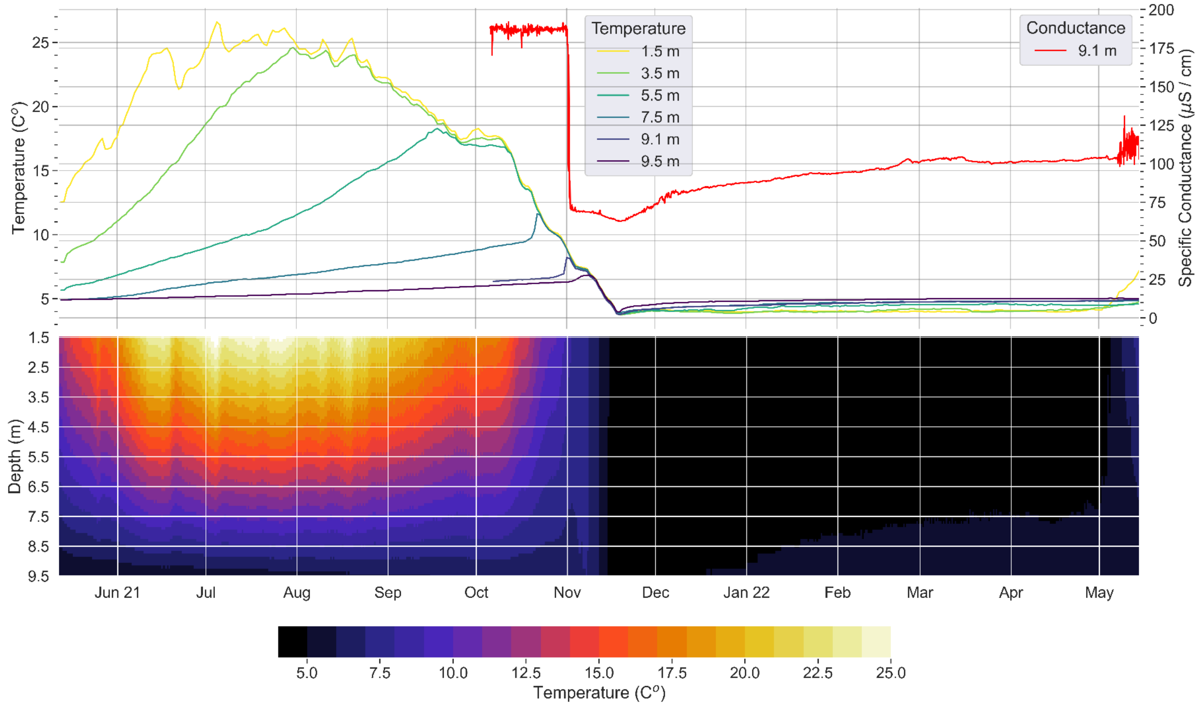

Figure 4. Hobo sensor data for temperature and conductance from Arco Lake, collected from May 2021 to May 2022 and from October 2021 to May 2022, respectively (top). Isotherm plot of the temperature data from the Hobo sensor (bottom).

Data from the temperature sensors (1.5, 3.5, 5.5, 7.5, 9.1, 9.5 m) and a conductance sensor (9.1 m) in Arco Lake from May 2021 to May 2022 are presented in Figure 4. In the summer of 2021, the temperature values in Arco Lake were different at distinct depths, representing the development of a summer thermocline. The temperatures at different depths started to converge in late fall until the lake became isothermal and continued cooling from 6 to 4 C in mid-November 2021, representing the erosion of thermal stratification. The Brunt-Väisälä or buoyancy frequency (N), commonly expressed as N^2 in units s^{-2}, calculated from the time series temperature data is near zero at that time, indicating an erosion of stability, which persisted until the sensors were removed on May 16, 2022, over a week after the ice-off on May

8 (Supplementary Figure 4). A drop in the conductance value at 9.1 m in early November 2021 preceded isothermal conditions and indicated mixing down to at least 9.1 m (Figure 4). The dimensionless lake number (Imberger and Patterson 1989) was calculated using the time series and hourly wind data from Itasca State Park (Supplementary Figure 5). It started to consistently rise on May 15, 2022 as the epilimnion warmed. In combination with the seasonally variable chemocline depth (Figure 3), these analyses indicate that Arco Lake mixes during isothermal periods and is not a meromictic lake. The data presented is most consistent with Arco being a dimictic lake, although holomixis cannot be ruled out.

Data from the temperature sensors (0.5, 2.5, 5.5, 8.5, 11.5, and 14.5 m) in Deming Lake from June 2019 to May 2020 are presented in Supplementary Figure 6. The lake became isothermal in early November 2019. The Brunt-Väisälä frequency calculated from this data dropped to near zero and rebounded slightly due to under-ice thermal stratification, a phenomenon not observed in Arco Lake (Supplementary Figure 4). The specific conductance profiles in Deming consistently show the same trend, although the exact depth and magnitude of the chemocline vary seasonally and on the decadal scale (Figure 3). This indicates partial seasonal mixing in Deming, likely during isothermal periods, but it may be insufficient or of too short a duration to fully mix the lake. Deming was ice-free on April 25, 2020 (Minnesota Department of Natural Resources 2022a), and the lake number started rising immediately due to the onset of thermal stratification (Supplementary Figure 5), likely limiting the opportunity for mixing. Long-term seasonal observation of a chemocline is consistent with Deming being a meromictic lake (Zadereev et al. 2017).

Arco presents an end-member of a seasonally mixed lake (dimictic or holomictic) and Deming an end-member of a meromictic lake among the four lakes studied here. In the absence of high-frequency sensor profiles for Budd and Josephine lakes, the Schmidt stability (Supplementary Figure 7) and the Brunt-Väisälä frequency (Supplementary Figures 8-11) were calculated from seasonal profiles of temperature (Supplementary Figure 12) and salinity for all four lakes. The Schmidt stability indicates that Deming and Budd are the most strongly stratified, followed by Josephine and Arco. It is unknown when ice came off Budd Lake in 2022, but Deming was ice-free on May 7, and Arco and Josephine were ice-free on May 8 (Minnesota Department of Natural Resources 2022a) following strong winds on the evening of May 7. Likely, Budd was also ice-free by May 8. A chemocline consistent with other summer observations was present on May 17, 2022, which could indicate a lack of spring mixing for Budd Lake. However, the January 2021 specific conductance profile for Budd shows a very weak and deep chemocline, which would be expected from an autumn mixing event. Without full profiles of specific conductance in Josephine Lake, it is impossible to evaluate mixing. However, based on existing profiles, if a chemocline persists through spring turnover in Josephine Lake as suggested by the sharp and deep chemocline observed in May 2022, then monimolimnion must be limited to depths below 11 m, representing only 3.6% of total lake volume (11,404.5 m^3 of 313,295.5 m^3).

Water color is related to the abundance of dissolved organic carbon (DOC) (Pace and Cole 2002). Of the four study lakes, Budd had the most colored water, followed by Deming (Supplementary Table 1). Arco and Josephine had very little color. Visually, Budd and Deming appear brown, while Arco and Josphine appear green. Enhanced water color could lead to a shallower thermocline and stronger stratification in Budd and Deming due to greater light absorption by compounds conferring color (Houser 2006). The Brunt-Väisälä frequencies, calculated from temperature and salinity profiles, are generally highest in the epilimnia during late summer (July 2021 and August 2022; Supplementary Figures 8-11). This indicates that temperature is more important than salinity to the stability of these lakes. In August 2022, when Deming Lake had the highest N^2 values observed, the meromictic stability (S') (Walker 1974) was 7.81 J m^{-2}, within the range observed for the meromictic and ferruginous Lake 120 in Canada (Campbell 1977) and Lake Nordbytjernet in Norway (Hongve 1999). These observations suggest that meromixis in Deming Lake is primarily due to thermal stratification, with a small contribution from salinity that could lead to meromixis in this lake but not the others nearby. This phenomenon could be common to dilute meromictic lakes. In fact, a mixing event was recorded for Deming Lake, in the summer of 1997, when a beaver dam west of the lake broke and flooded it (Frane and Walberg 1997), indicating mixing can occur due to catastrophic events.

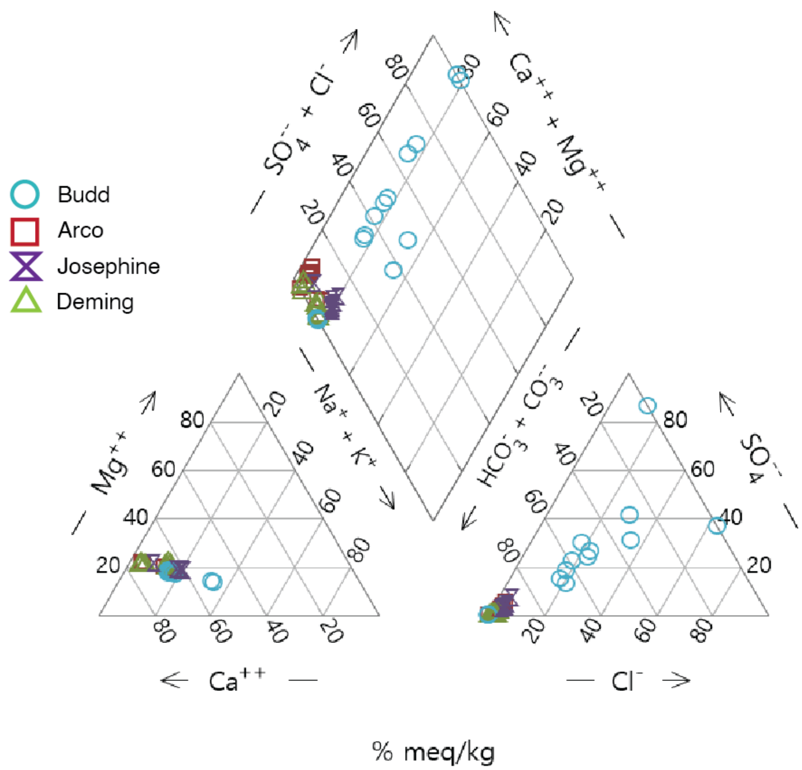

Figure 5. Piper Diagram of major cations and anions collected in May 2021.

Chemical Characteristics and Water Sources

A Piper diagram was used to define the water types of the four lakes based on their major cations and anions. The predominant cation in all four study lakes was calcium (Figure 5). Budd had a greater proportion of milliequivalents from sodium and potassium than the other three lakes, balanced mostly by magnesium. Bicarbonate and carbonate ions represent nearly all anion milliequivalents in Deming, Arco, and Josephine whereas chloride and sulfate contribute to the anion balance in Budd. The water type for Deming, Arco, and Josephine is a calcium-bicarbonate type, whereas Budd does not have a dominant water type. The low specific conductance and lack of water type in Budd indicate the water source is predominantly precipitation. Calcium, magnesium, and carbonate/bicarbonate ions source from the calcareous Itasca moraine and are typical for the Itasca region (Megard et al. 1993). This indicates that water supplying Deming, Arco, and Josephine has undergone more water-rock reaction than that supplying Budd, such as might be expected from an increasing proportion of groundwater seepage to a lake's water inputs. Deming, Arco, and Josephine lie in a tunnel valley channel containing coarser sands and gravel while Budd Lake is poorly integrated hydrologically with the other three lakes, and the net seepage in Budd is probably the lowest among all the lakes. Arco (465.8 MAMSL) is located 51 meters north of Josephine (465.4 MAMSL) and Deming (464.8 MAMSL) is located 284 meters north of Arco. The similar lake levels and wetlands between Arco and Deming (Figures 1 and Supplementary Figure 1) indicate these lakes are likely to be hydrologically connected. If the water table mimics the surface topography, groundwater potentially flows from Arco-Josephine to Deming. However, Budd (478.6 MAMSL) is perched highest in the watershed, located off-axis of Deming-Arco-Josephine, to the west of a ridge (Figure 1). Because it is perched, the ridge is likely composed of less permeable material than the valley sediments, such as till. The presence of wetlands on the north end of Budd that follow a small valley towards Deming suggests that there could be a surface or near surface hydrological connection from Budd to Deming. Lakes highest in their watershed are more likely to receive a greater proportion of water from precipitation (Kratz et al. 1997), consistent with the dilute nature of Budd Lake.

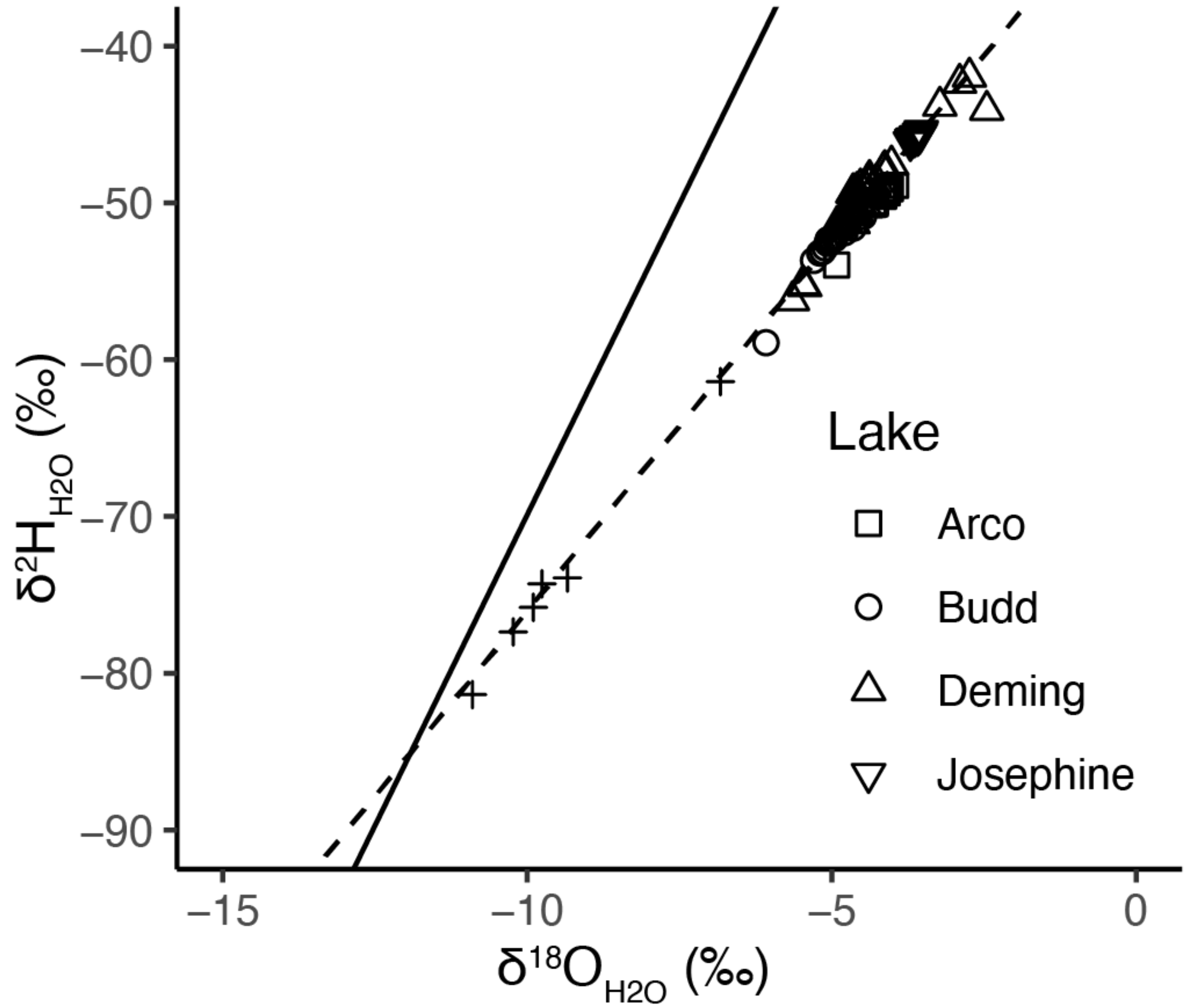

Figure 6. Isotope data and fit (dashed line) of an evaporation line ($\delta^2H_{H2O} = 4.5*\delta^{18}O_{H2O} - 29.9$, r-squared = 0.93) from the four study lakes plotted with a Local Meteoric Water Line (Stelling et al., 2021 Marcell Exp Forest). Crosses are spring or bog water data from Itasca State Park (Supplementary Table 1). The cross closest to the lake data points is the Deming bog. Analytical precision is within the symbol sizes.

The isotopic composition of water (i.e., δ^2H_{H2O} and $\delta^{18}O_{H2O}$ in ‰) in May 2021 varied little with depth in each lake (Supplementary Figure 13). In Arco, Budd, and Deming sampled in

June 2019, the epilimnion waters become depleted relative to the deeper water. Additional measurements at Deming Lake in July and October 2021 show enriched values in the epilimnion relative to the surface. Preferential evaporation of light isotopes during the summer and early fall drive the epilimnion to more enriched values. In Figure 6, all lakes data points diverge from a local meteoric water line (LMWL; Stelling et al. 2021) on a lake evaporation line (LEL) with equation δ^2H_{H2O} (‰) = 4.5*$\delta^{18}O_{H2O}$ (‰) - 29.9. The intersection of the LMWL and the LEL is the composition of regional groundwater, representing isotopically depleted snowmelt as the predominant pathway for recharging the local aquifers (Krabbenhoft et al. 1994).

Historical δ^2H_{H2O} and $\delta^{18}O_{H2O}$ data from springs at Elk Lake were retrieved from the Minnesota Spring Inventory (Minnesota Department of Natural Resources 2022b). The Elk Lake springs were sampled again in May 2022, as well as a sample from Nicollet Creek and the bog on the southeast side of Deming (Supplementary Table 1). These sites had abundant marsh marigolds (Supplementary Figure 14), which bloom in May at groundwater discharge sites (Rosenberry et al. 2000). The sites at Elk Lake and Nicollet Creek had visible iron mineralization, indicating reducing, iron-bearing water discharge at the surface (Supplementary Figure 14). The Nicollet Creek spring sample lies closest to the intersection of the LEL and LMWL, whereas the Deming bog sample lies closest to the lakes but is more enriched than the lakes (Figure 6).

The seasonal amplitude of a lake's isotopes can be used to calculate a lake's water residence time (Engel and Magner 2019). A time series of temperature data from weather station ITCM5 was used to determine average daily temperatures, and seasonal maximum and minimum values were used to calculate the amplitude in $\delta^{18}O_{H2O}$ inputs of precipitation. The Deming Lake $\delta^{18}O_{H2O}$ values (Supplementary Figure 13) encompass early spring, mid-summer, and late summer data, and were used to determine the seasonal amplitude in $\delta^{18}O_{H2O}$ (Supplementary Figure 15). These two values were used to estimate a mean water residence time of 100 days for Deming Lake.

Biological Characteristics

Prior work on these four lakes indicated the presence of a lake-wide turbidity maximum layer that was persistently just below 5 m Deming Lake (Baker and Brook 1971). This peak was observable between late May and August from 1968-1970 but was absent in the winter. It was reported in that study that bacteria and phytoplankton both contributed to the turbidity maximum based on microscopic observations. This work indicated the layer was populated by the cyanobacteria *Oscillatoria agardhii* var. *isothrix* (this genus is now called *Planktothrix*).

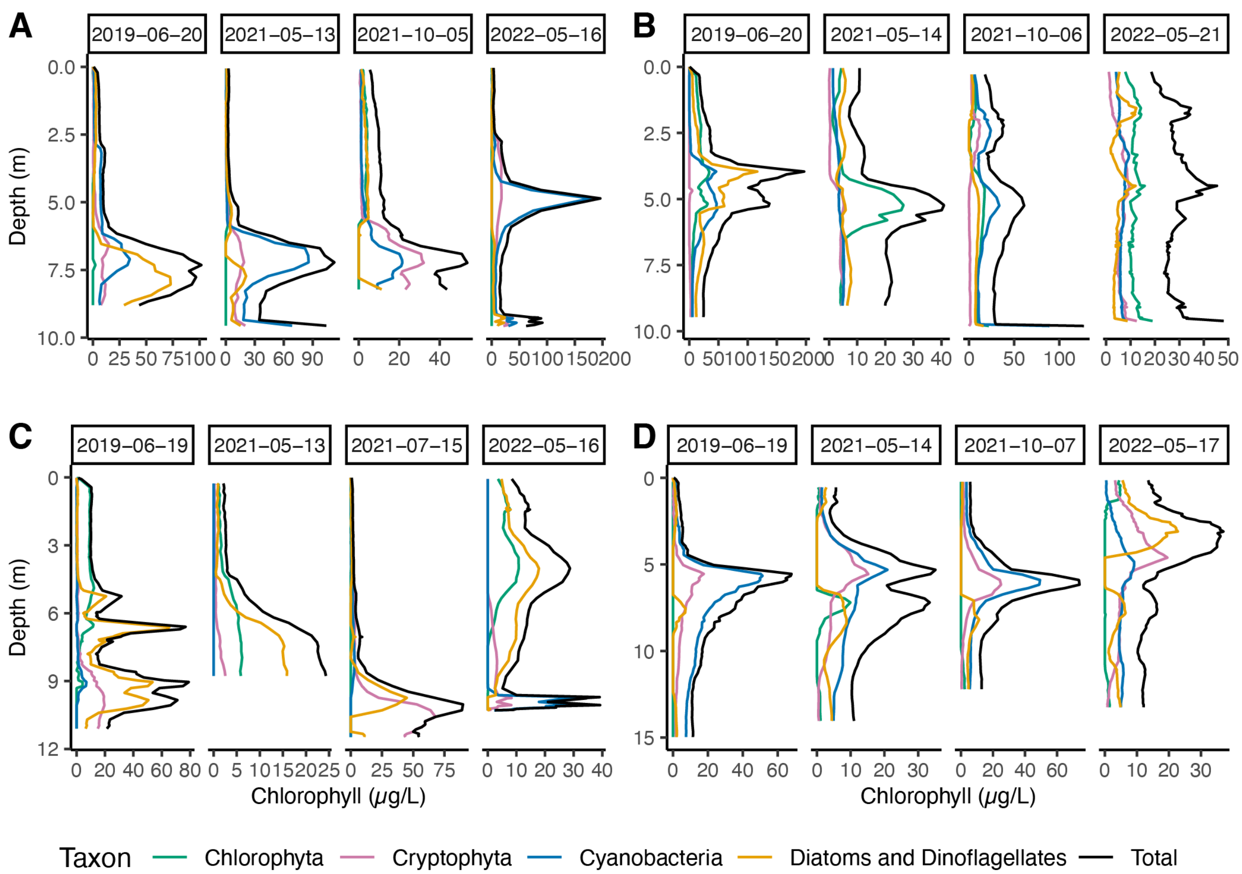

Figure 6. Multi-wavelength chlorophyll fluorescence (i.e. Fluoroprobe) measurements at a) Arco, b) Budd, c) Josephine, and d) Deming Lakes, showing seasonal and depth trends in major taxonomic groups. Note that the x scales vary between plots.

From 2019 to 2022, chlorophyll-a measured via multi-wavelength fluorescence acquired with a Fluoroprobe allowed for deconvolution of the fluorescence signal so chlorophyll-a could be attributed to one of four taxonomic groups: Cyanobacteria, Chlorophyta, Diatoms and Dinophyta, or Cryptophyta. Taxon-specific concentrations of chlorophyll-a in each lake inform phytoplankton community structures with depth (Figure 6). Deming Lake has a persistent SCML around 5-6 m attributable to Cyanobacteria. The SCML is less distinct in May 2022, a week and a half after ice off. It was also less distinct in May 2021. This suggests that the SCML in Deming

Lake is a summer phenomenon that develops at or below the thermocline (Supplementary Figure 12), consistent with the observations from Baker and Brook (1971). In June 2019, a profile of photosynthetically active radiation was also recorded (Supplementary Figure 19), and showed an inflection point at 5.5 m, corresponding to the depth of the SCML at that time. These observations are consistent with cyanobacteria forming a dense accumulation at that depth, attenuating the light flux into deeper waters.

Samples from the SCML were taken from the four lakes in May 2022: Arco (5 m), Budd (4.5 m), Deming (3.5 m), and Josephine (4.5 m). The most common phytoplankton of the four lakes were the cyanobacteria *Planktothrix* sp. and *Aphanocapsa* sp., and the green alga *Monoraphidium* sp. (Supplementary Figure 17). Some other phytoplankton species identified were the red alga *Cryptomonas* sp., the cyanobacteria *Planktolyngbya* sp. and *Dolichospermum* sp., as well as other colonial green algae and cyanobacteria species.

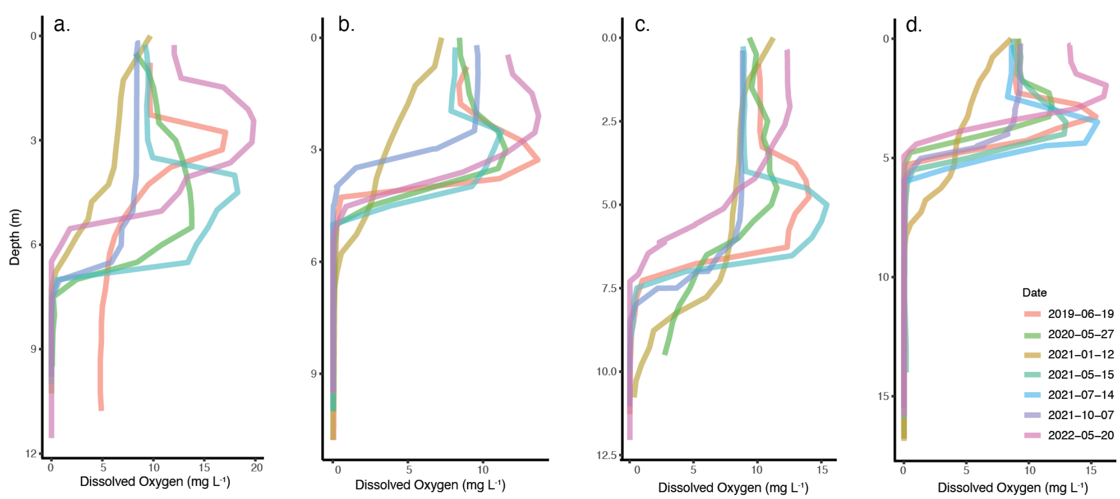

Figure 7. Dissolved oxygen measurements at a) Arco, b) Budd, c) Josephine, and d) Deming Lakes, showing seasonal and depth trends.

All four lakes have subsurface oxygen maxima exceeding air saturation during the summer but lack this feature in the fall (Figure 7). The subsurface oxygen maximum in Deming Lake usually occurs at 4 m, near the top of the thermocline (Church et al. 1989; Supplementary Figure 12; Bieter et al. 1991; Balk et al. 2007). Metalimnetic oxygen maxima can result because dissolved oxygen is more soluble in cold water after spring mixing, but as the water warms the gas solubility decreases, causing oxygen to become supersaturated. Stratification induced by the thermocline then limits the discharge of supersaturated oxygen to the atmosphere (Wilkinson et al. 2015). Deming Lake rapidly develops a thermocline after ice-off (Supplementary Figure 6), providing a mechanism for gas trapping. Enhanced biological productivity can also contribute to the oxygen maximum, but is generally a smaller contributor (Craig et al. 1992; Wilkinson et al. 2015). The subsurface oxygen maximum is above the SCML in Deming Lake, suggesting that the entrainment of spring oxygen is a larger contributor than photoautotrophy to the oxygen maximum. However, there is also a pH maximum at that depth during the summer (Supplementary Figure 18; Church et al. 1989; Barkow and Habedank 1990; Bieter et al. 1991), as is expected for active photoautotrophy. Itasca Biological Station and Laboratories student experiments that quantified photosynthesis and respiration via dissolved oxygen measurements in bottle experiments generally found that net oxygen release was minimal in the SCML due to vigorous respiration (Engstrom et al. 1974; Barkow and Habedank 1990). Measurements of the O_2/Ar ratio would help to quantify the contribution of the two processes to the subsurface oxygen maximum (Craig et al. 1992).

The occurrence of a summer SCML in Arco, Budd, and Josephine Lakes was more variable than in Deming Lake (Figure 6). Arco had a spring bloom of cyanobacteria in May 2021 and in May 2022, at which time the highest chlorophyll-a of this study was recorded. At both times, the SCML occurred below the oxygen maximum, in a hypoxic zone of the water column. The May 2022 SCML at 5 m in Arco also enhanced light attenuation below that depth (Supplementary Figure 19), as was observed in Deming in June 2019.

Arco, Budd, and Josephine also have subsurface oxygen maxima during summer, although not as consistently as Deming. When the depth of the thermocline is plotted against the depth of the oxygen maximum for all four lakes, there is a significant correlation if October 2021 samples are excluded (Supplementary Figure 20). In the fall, the subsurface oxygen maximum is absent (highest values are at the surface), and the thermocline is deepest (Figure 7). This may reflect that in fall the thermocline has deepened into hypoxic or anoxic waters.

Conclusion

Although reported to be meromictic, based on seasonal temperature and specific conductance profiles, Arco, Budd and Josephine may be holomictic or even dimictic. Deming has been meromictic in the periods of data collection presented here (2006-2009 and 2019-2022) but experienced a mixing event in 1997 when an adjacent beaver dam broke. Although a seasonally persistent chemocline occurs in Deming Lake, stratification is predominantly a thermal phenomenon, with stability mostly conferred by a thermocline that develops rapidly after isothermal spring and fall periods. Thermal stratification is not typical of meromictic lakes in the temperate zone, but this weak stratification may be common in dilute boreal lakes (Meriläinen 1970; Campbell 1977). However, such meromixis may be easily perturbed by hydrographic or land-use changes (Hongve 2002).

The chemical composition of the study lakes reflects their position in the watershed and water sources. The highest-elevation lake, Budd, had no distinguishable water chemical type and likely received most of its water from precipitation. Deming Lake had the highest ionic load, consistent with a greater contribution of water that had undergone some water-rock interaction, likely groundwater. Further work is necessary to characterize groundwater composition and quantify and localize groundwater input to determine if Deming Lake could be classified as crenogenic meromictic. The short water residence time in Deming Lake implied by the analysis of δ^2H_{H2O} and $\delta^{18}O_{H2O}$, along with the minimal surface water inputs and likely high permeability of tunnel valley deposits suggest the shallow groundwater system should be considered as a major water source.

All four lakes have SCML during summer. The depth of the SCML varies in Arco, Budd, and Josephine and is sometimes absent, but persists at around 5 m in Deming, corresponding to the base of the photic zone. Subsurface oxygen maxima above air saturation likely develop by trapping gas in cold water that then warms with rapid thermocline development in the spring. Corresponding pH maxima in Arco and Deming indicate that primary productivity could also contribute to the subsurface oxygen maxima.

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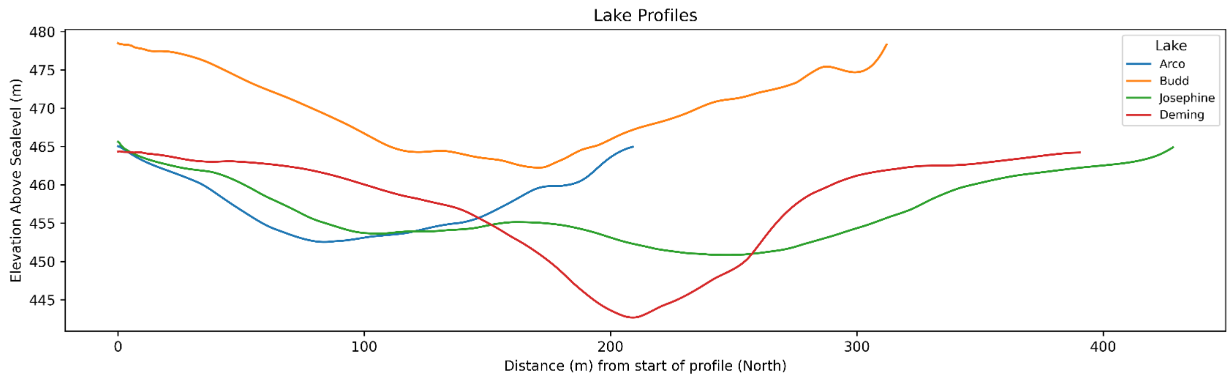
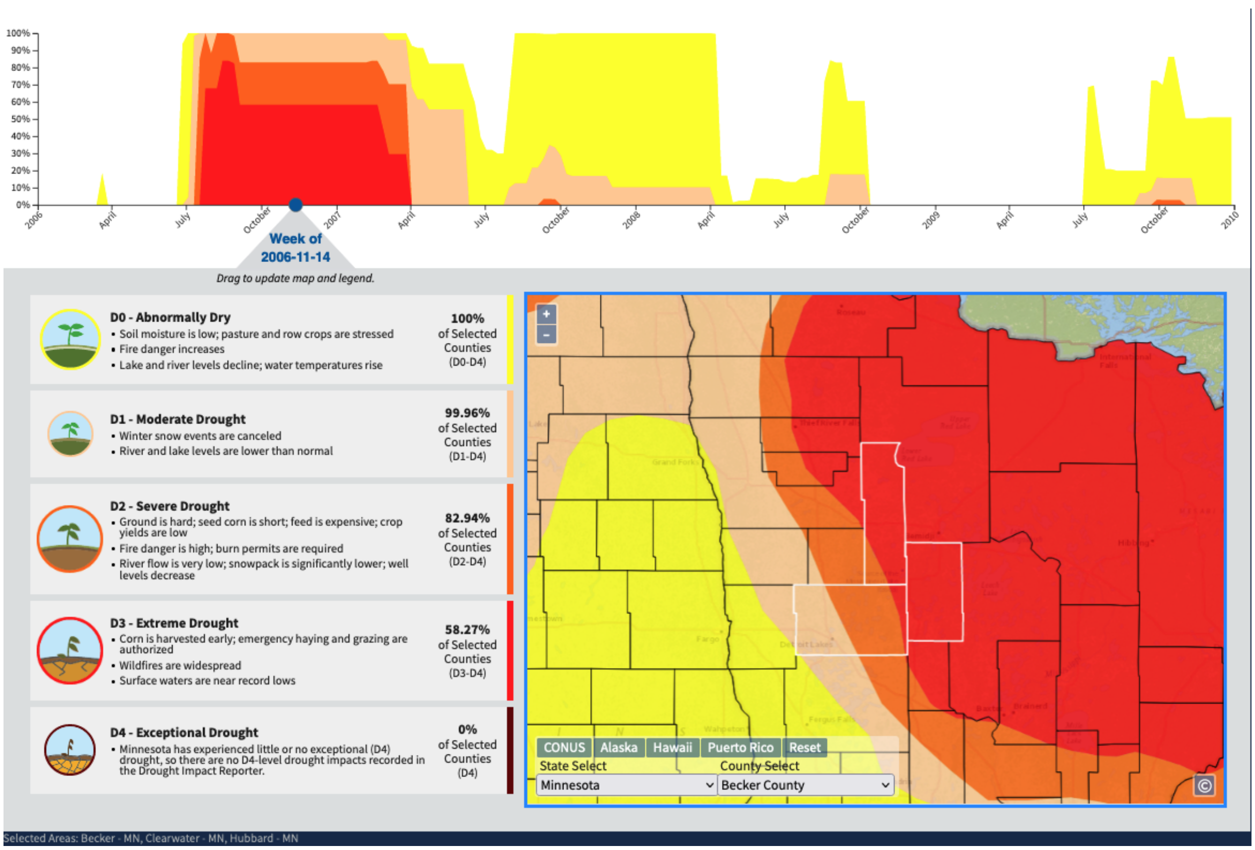
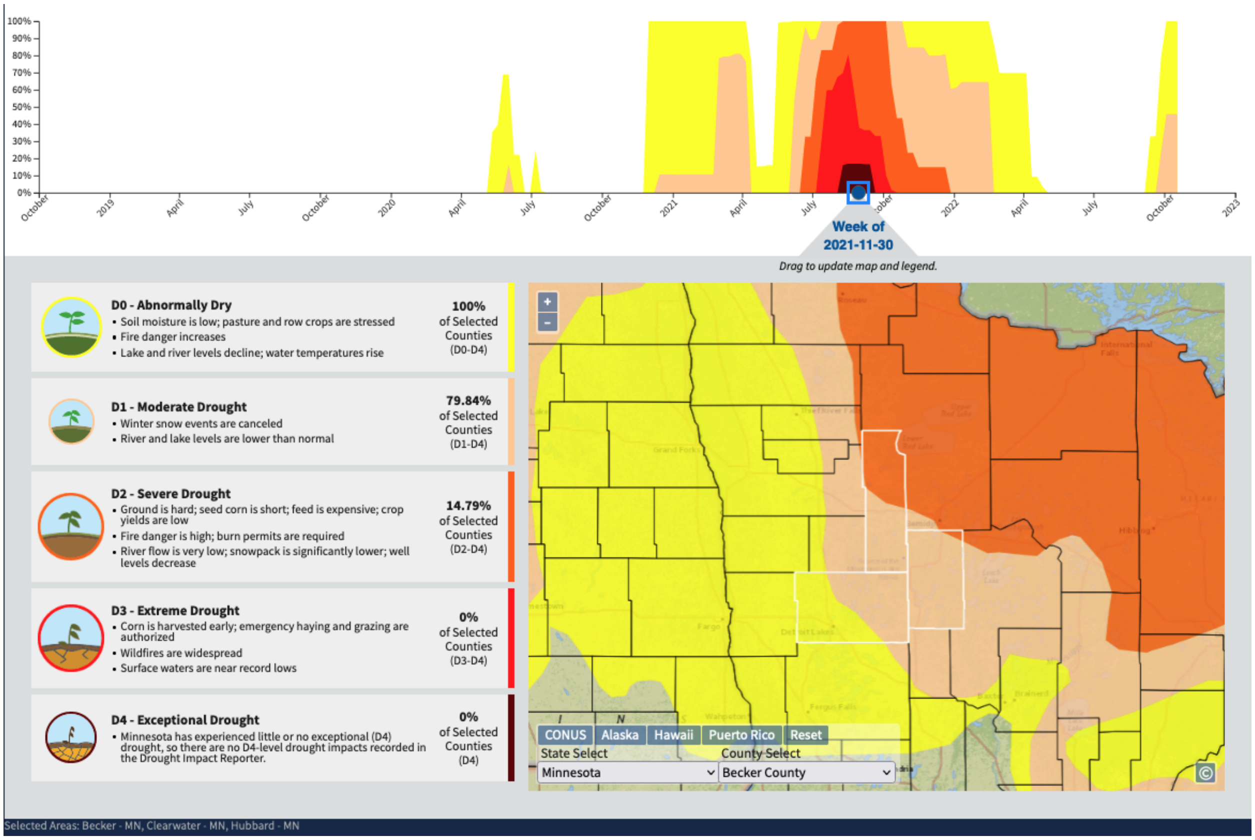


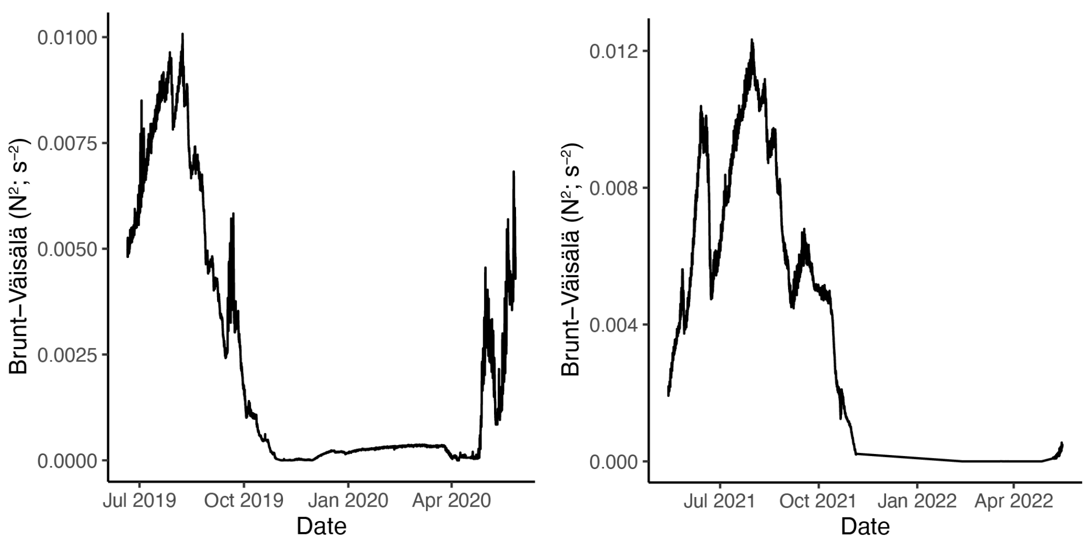
Supplementary Figure 1. Profiles of the lakes (in meters above mean sea level) along the fence diagrams in Figure 1.



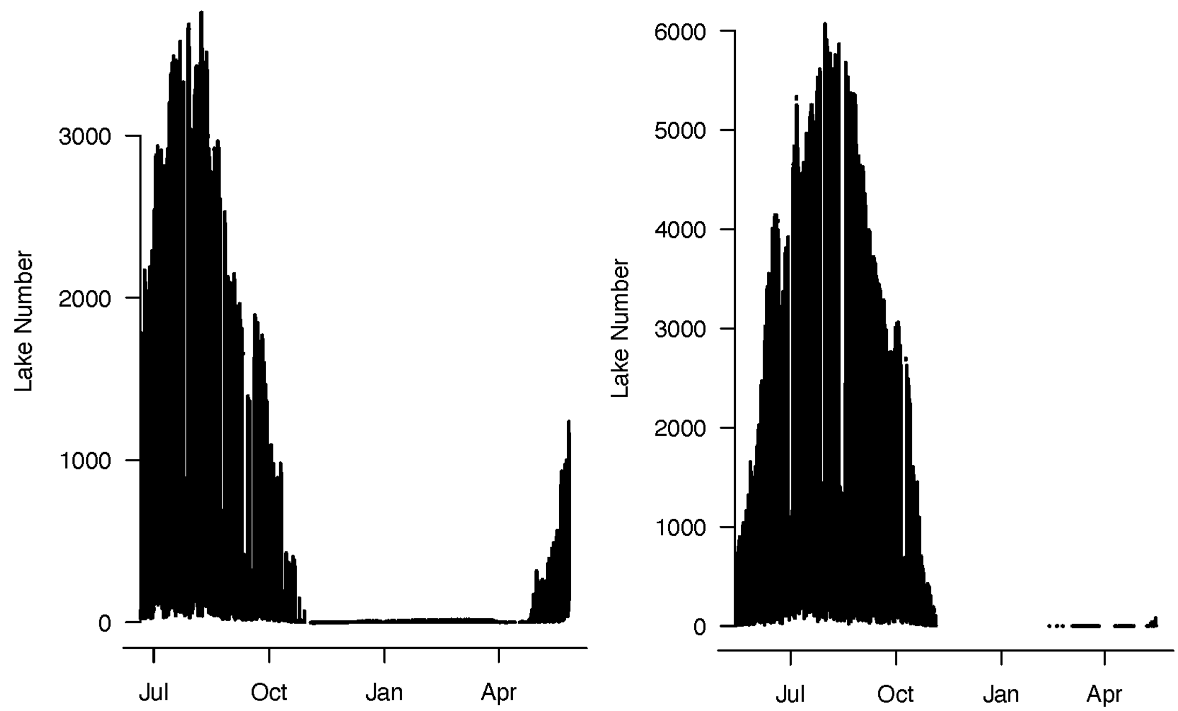
Supplementary Figure 2. Historical drought information for the counties encompassing Itasca State Park during the period of data collection from 2006-2009.



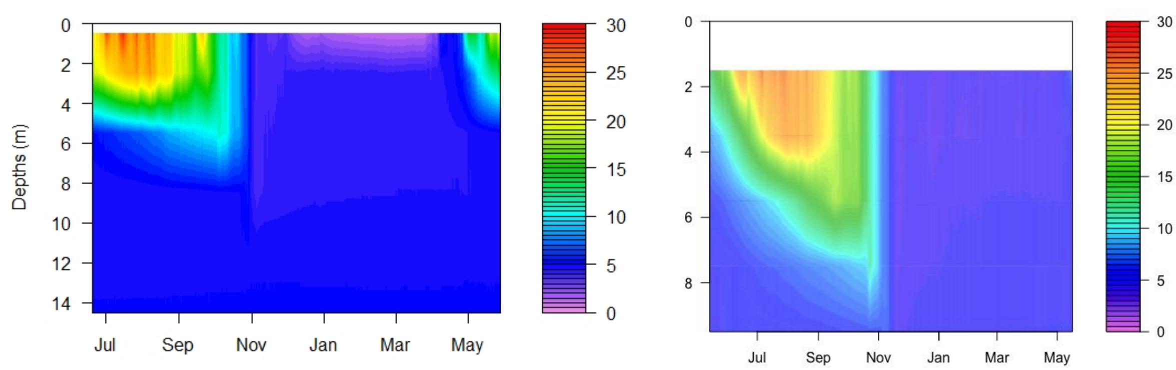
Supplementary Figure 3. Historical drought information for the counties encompassing Itasca State Park during the period of data collection from 2019-2022 (retrieved on October 24, 2022).



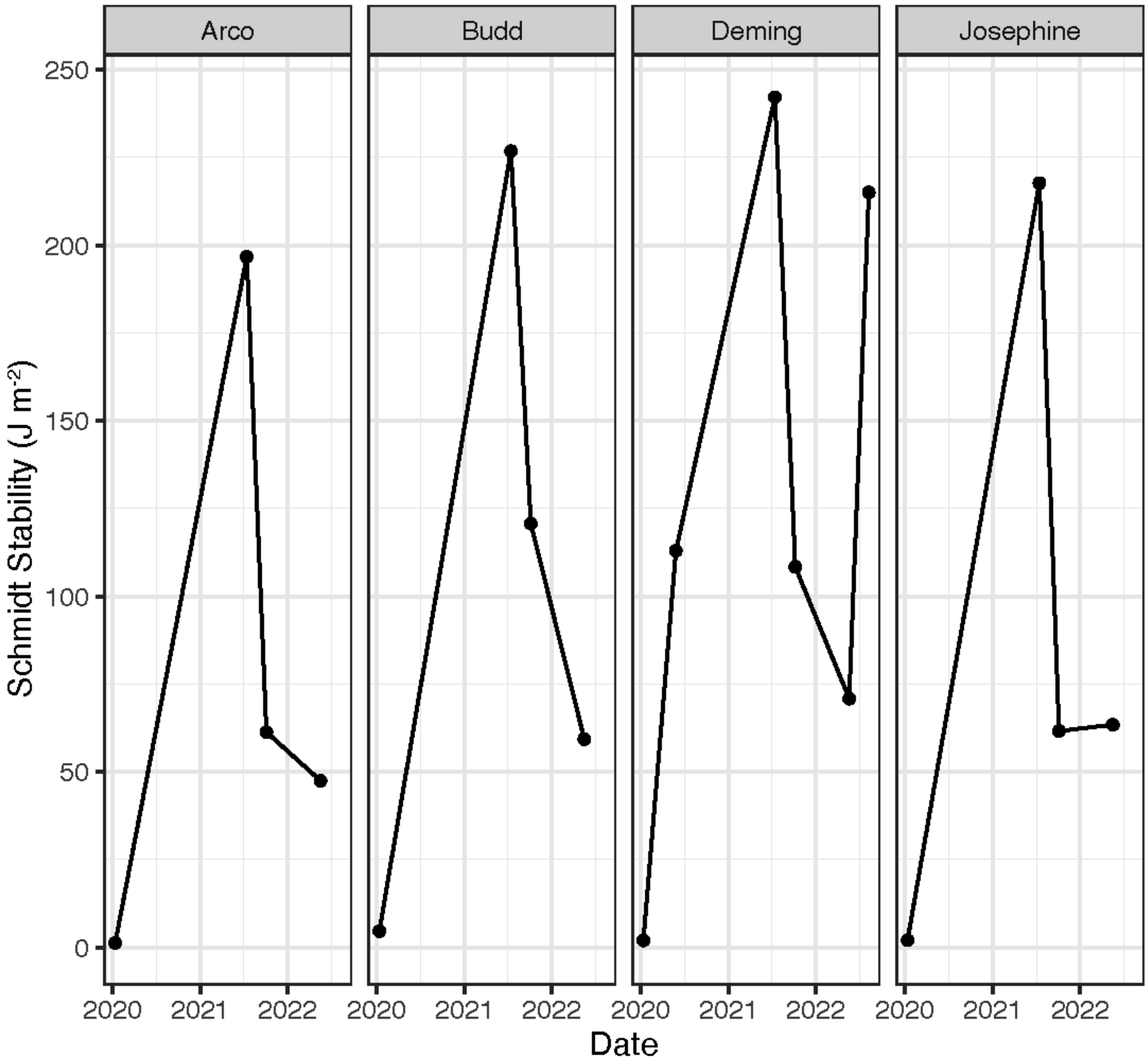
Supplementary Figure 4. The Brunt-Väisälä or buoyancy frequency (N^2, s^{-2}), calculated from the temperature time series for Deming Lake from June 2019 to May 2020 (left), and Arco Lake from May 2021 to May 2022 (right). Higher values indicate greater stability.



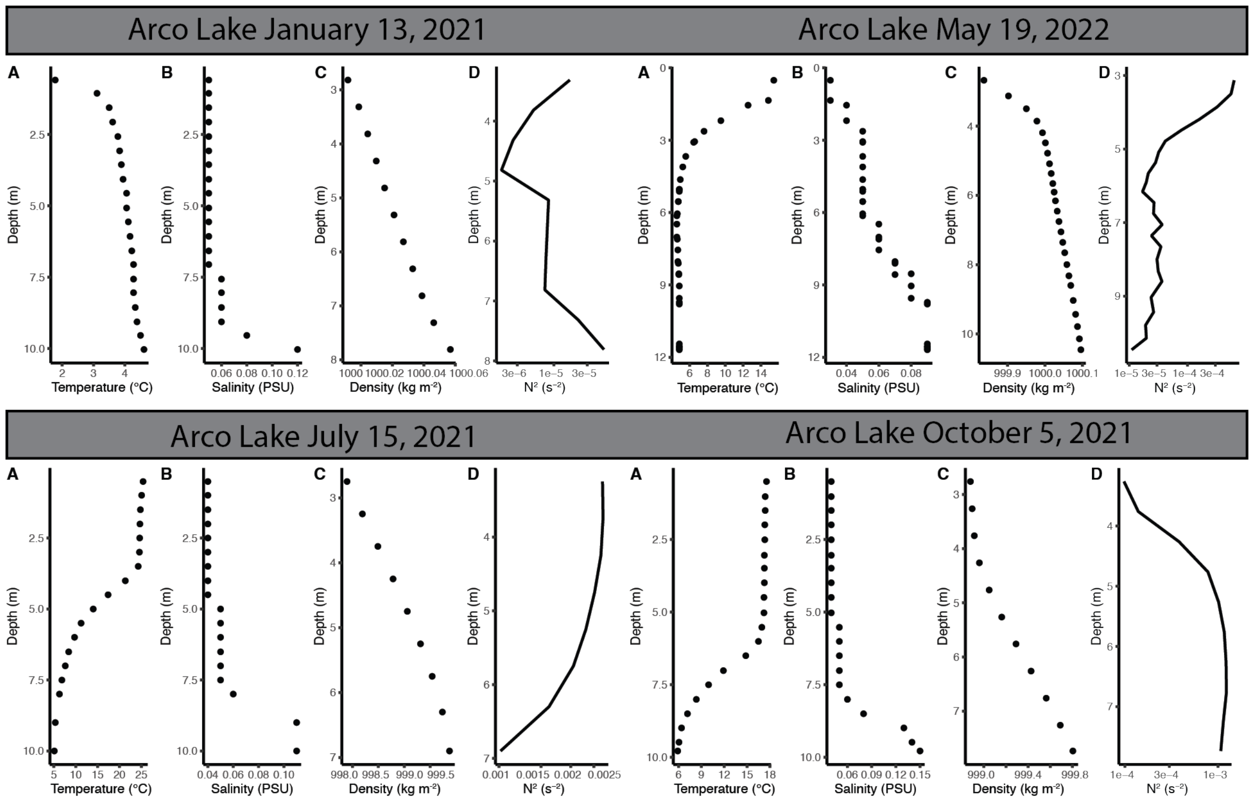
Supplementary Figure 5. The dimensionless lake number was calculated using wind speeds from the ITCM5 weather station and the temperature time series for Deming Lake from June 2019 to May 2020 (left), and Arco Lake from May 2021 to May 2022 (right). Higher values indicate greater stability.



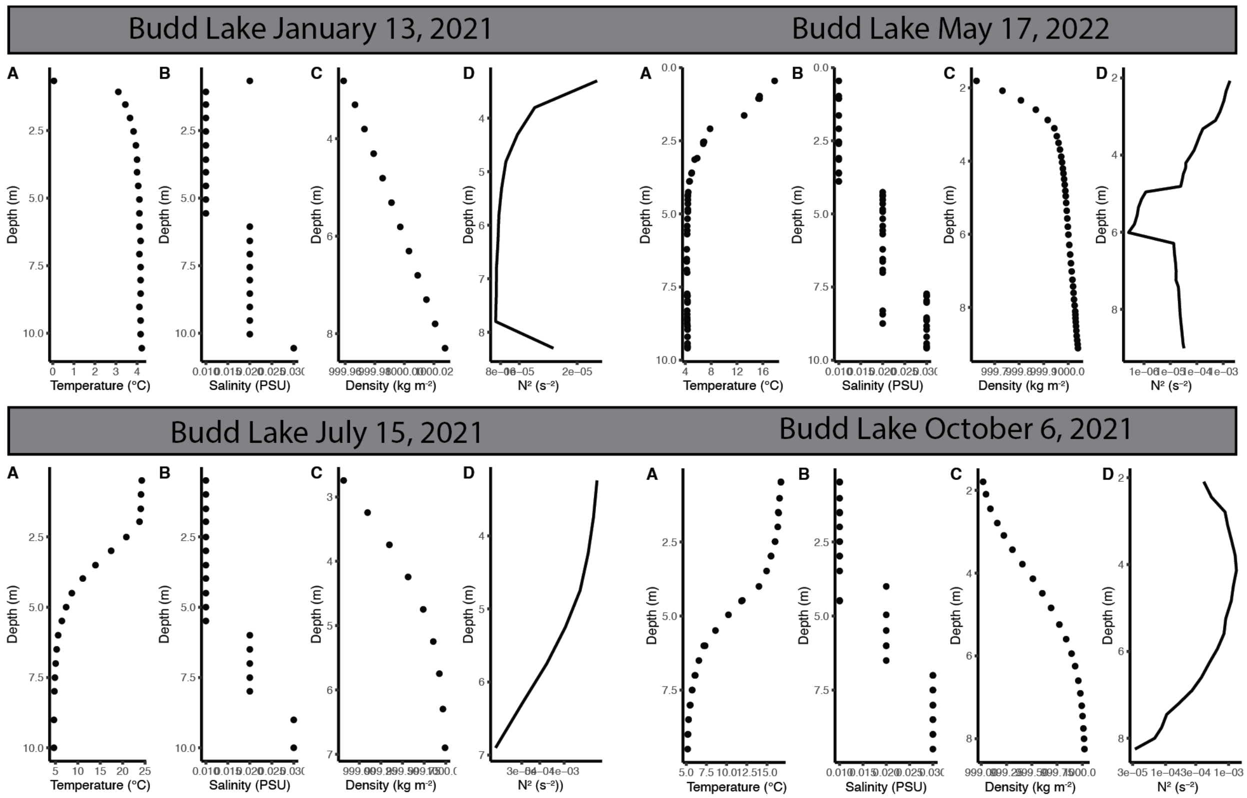
Supplementary Figure 6. Deming Lake temperatures (C) from June 2019 to May 2020 (left). Arco Lake temperatures (C) from May 2021 to May 2022 (right).



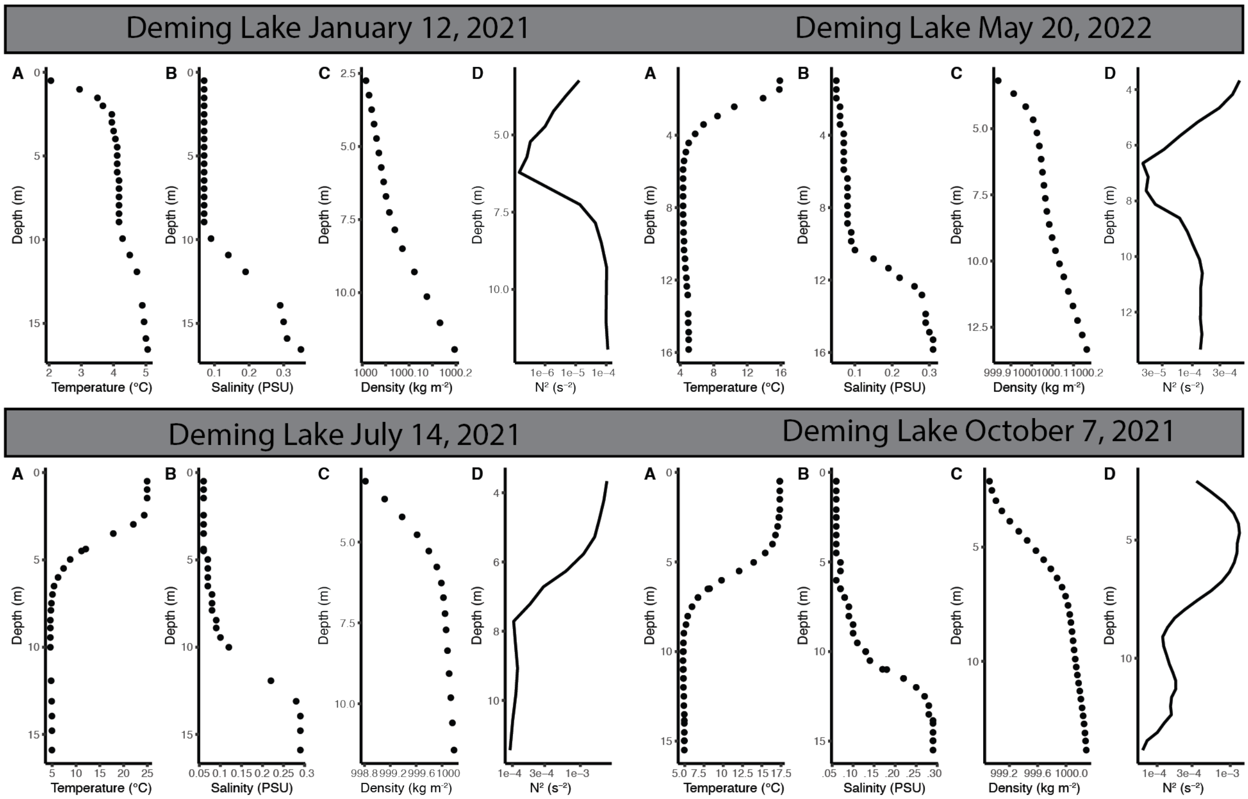
Supplementary Figure 7. Plots of Schmidt Stability for each of the four study lakes from January 2021 to August 2022. Higher values indicate greater stability.



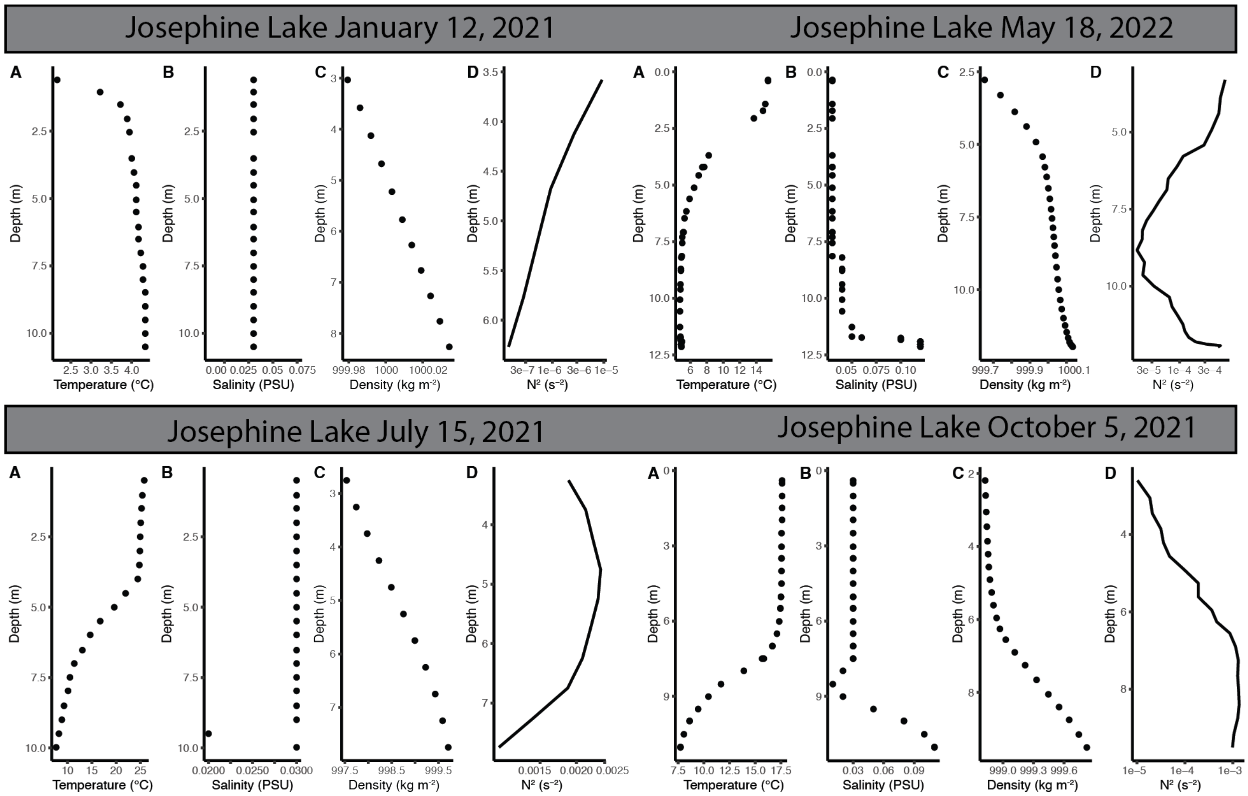
Supplementary Figure 8. The Brunt-Väisälä or buoyancy frequency (N^2, s^{-2}), calculated from the temperature and salinity profiles from Arco Lake from January 2021 to May 2022. Higher values indicate greater stability.



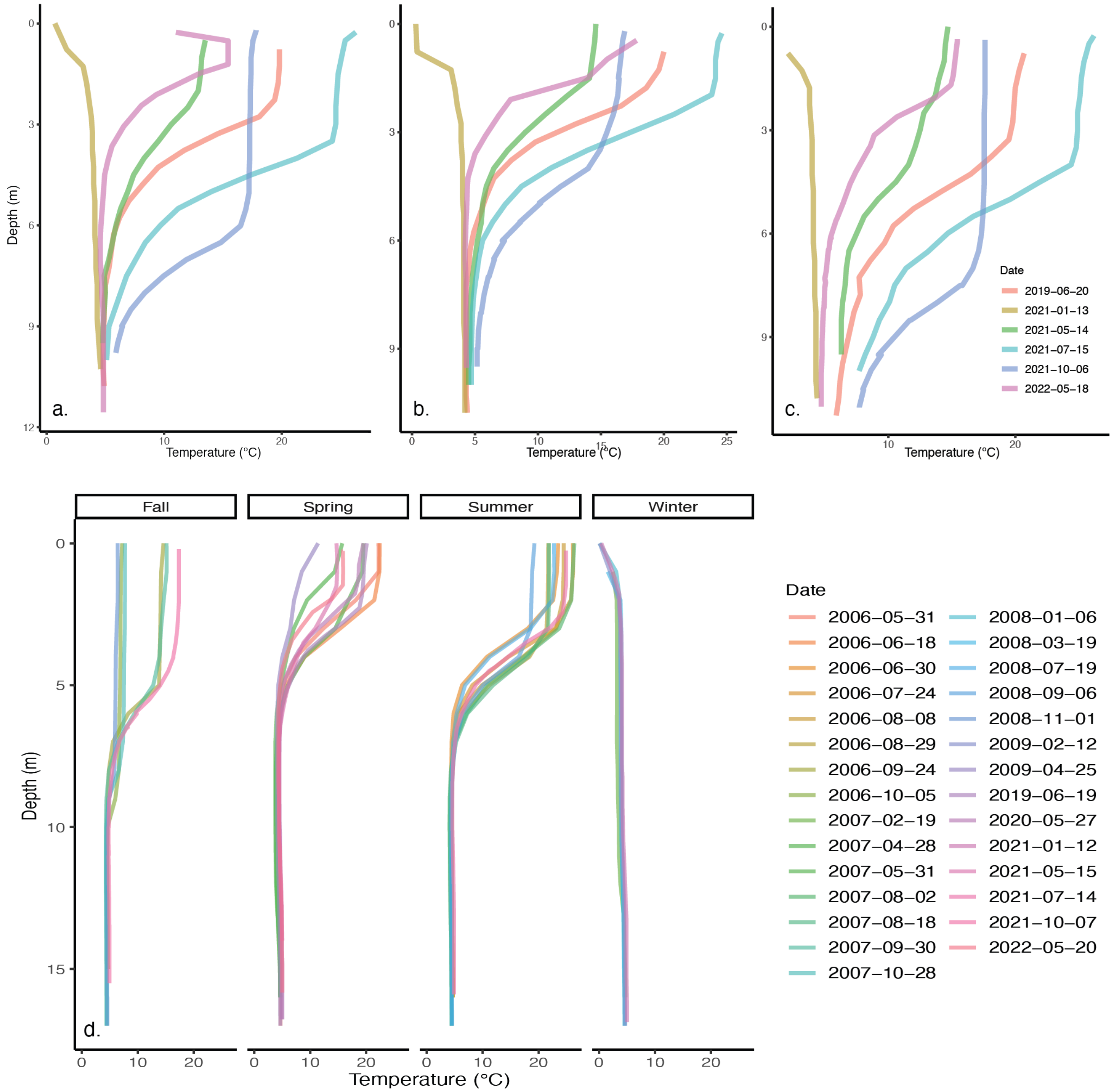
Supplementary Figure 9. The Brunt-Väisälä or buoyancy frequency (N^2, s^{-2}), calculated from the temperature and salinity profiles from Budd Lake from January 2021 to May 2022. Higher values indicate greater stability.



Supplementary Figure 10. The Brunt-Väisälä or buoyancy frequency (N^2, s^{-2}), calculated from the temperature and salinity profiles from Deming Lake from January 2021 to May 2022. Higher values indicate greater stability.



Supplementary Figure 11. The Brunt-Väisälä or buoyancy frequency (N^2, s^{-2}), calculated from the temperature and salinity profiles from Josephine Lake from January 2021 to May 2022. Higher values indicate greater stability.

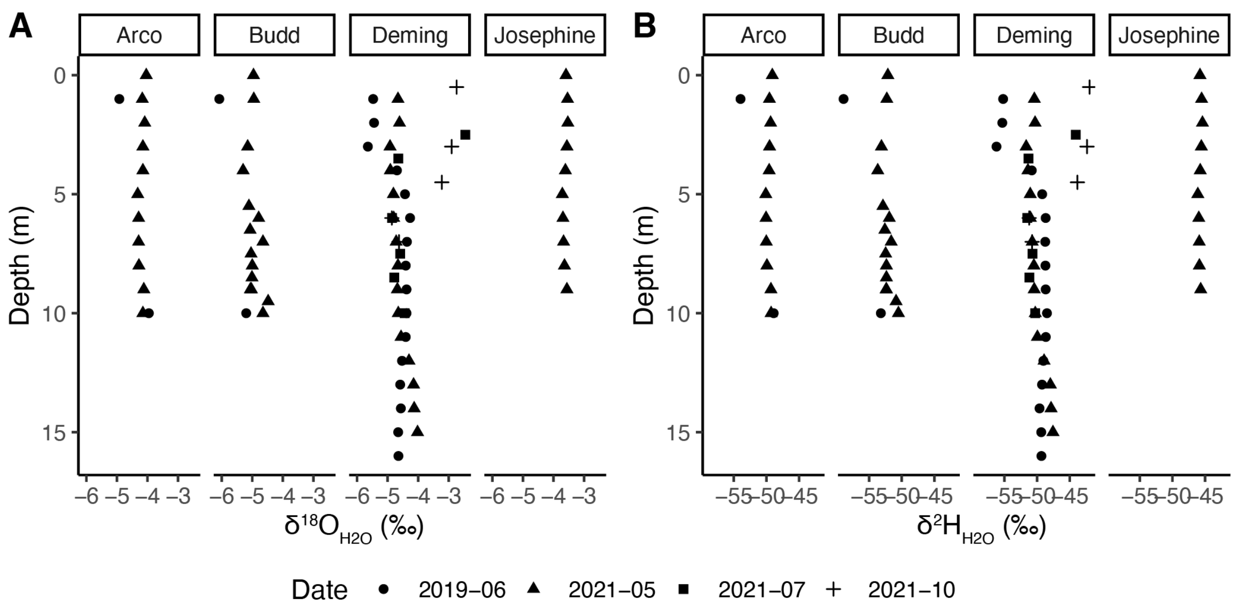


Supplementary Figure 12. Temperature profiles of a) Arco Lake, b) Budd Lake, c) Josephine Lake, and d) Deming Lake. For Deming Lake, seasons were classified according to solstice and equinox dates.

Supplementary Table 1. Water color in mg Pt L^{-1}. The depths of individual samples (in meters) are given in parentheses.

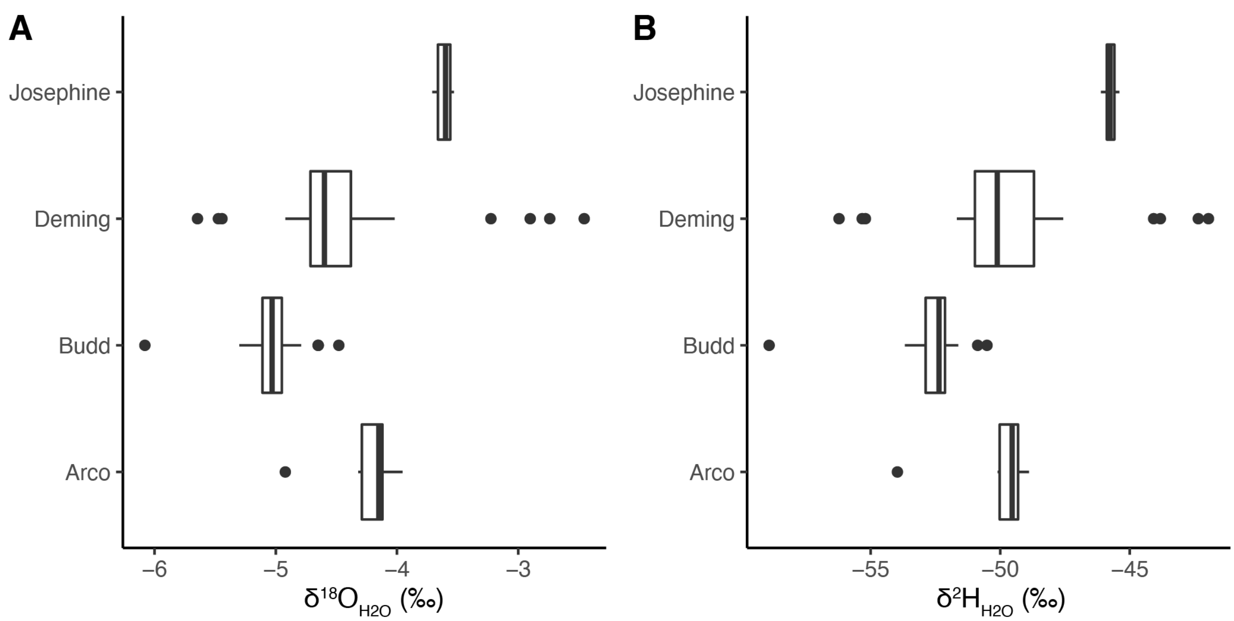
	Arco	Budd	Deming	Josephine
Depth 1	1.4 (4)	32.87 (2)	8.0 (3.5)	3.1 (2)

Depth 2	3.1 (5)	27.9 (4.5)	8.0 (4.5)	1.4 (4.5)
Depth 3	4.71 (5.5)	24.6 (9)	8.0 (5)	1.4 (9)
Average	3.1	28.4	8.0	2.0
Standard dev.	1.7	4.2	0	1.0



Supplementary Figure 13. Trends in $\delta^{18}O_{H2O}$ and $\delta^{2}H_{H2O}$ with depth in the four study lakes. Deming was the only lake sampled in all seasons. Analytical precision is within the symbol size.

Supplementary Figure 14. Left: marsh marigold in boggy areas around Deming Lake with 3x4" field notebook for scale. Righ: iron mineralization at Elk springs.

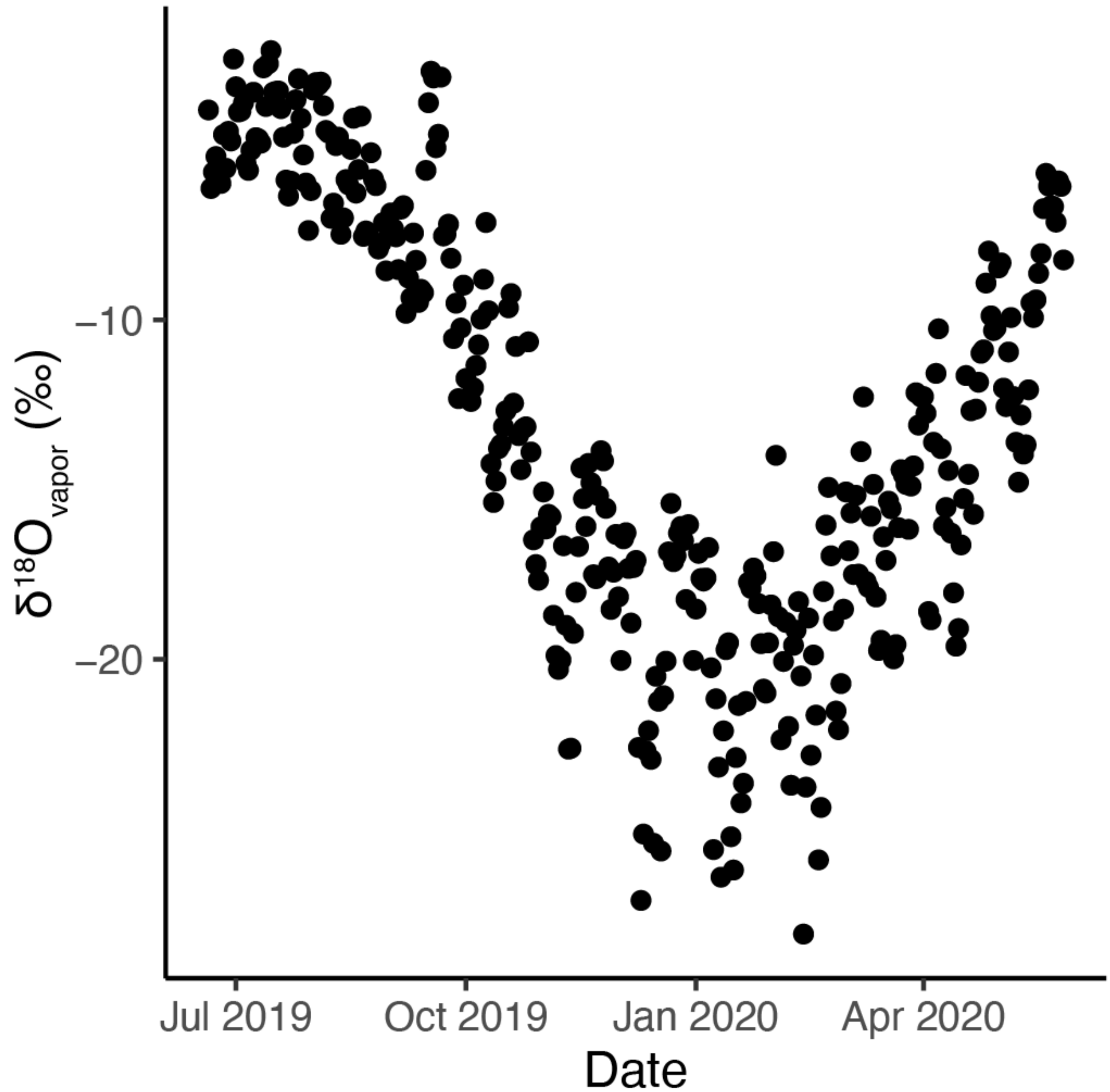


Supplementary Figure 15. The range of $\delta^{18}O_{H2O}$ and $\delta^{2}H_{H2O}$ in the four study lakes for the periods specified in Supplementary Figure 13.

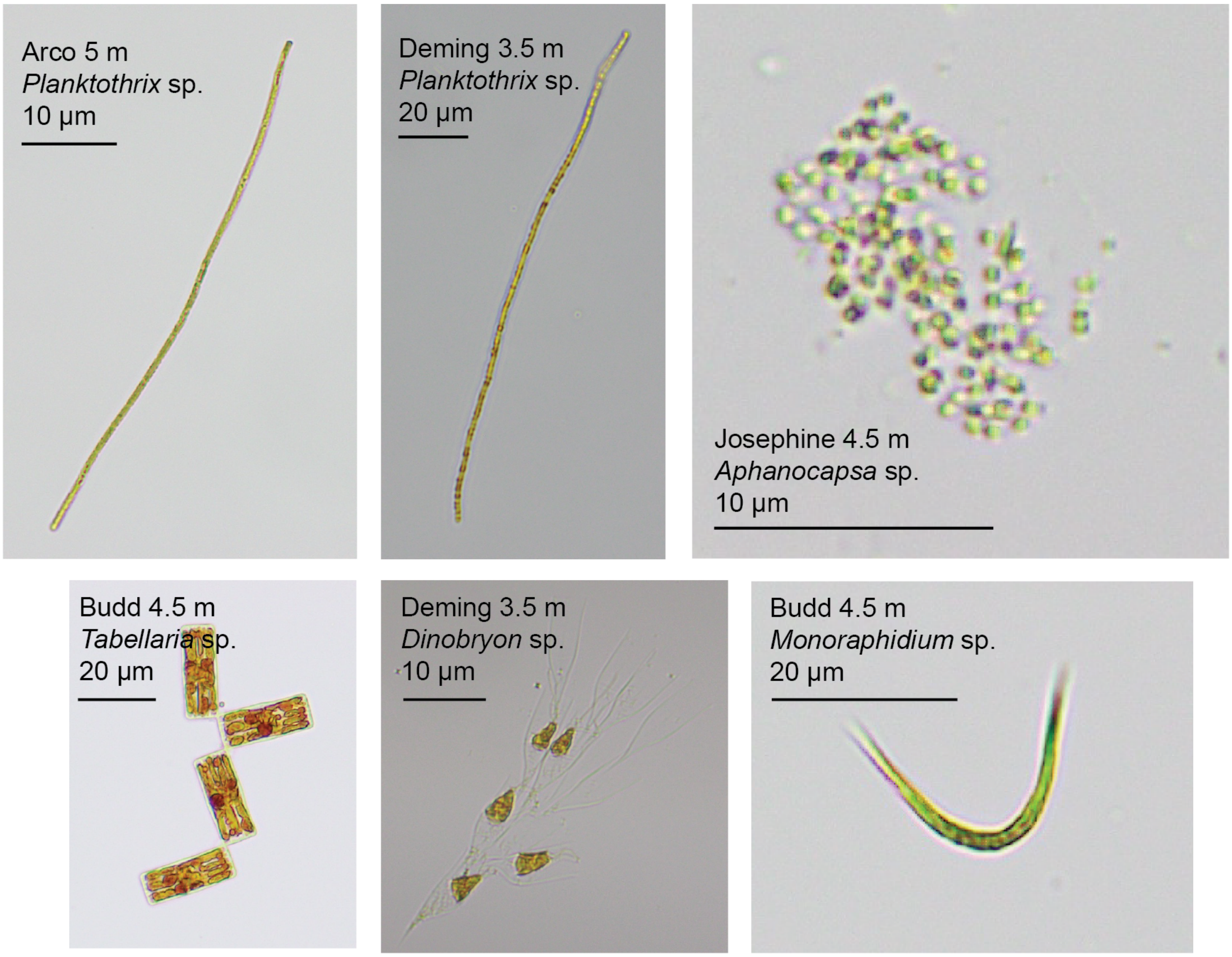
Supplementary Table 2. Stable isotopes of spring and bog water.

Site Name	Latitude	Longitude	$\delta^{18}O_{H2O}$ (‰)	$\delta^{2}H_{H2O}$ (‰)
Deming Bog	47.169440	-95.167162	-6.83	-10.90
Nicollet Creek	47.193874	-95.230539	-10.90	-81.36
Elk3	47.190478	-95.211350	-10.23	-77.36
Elk4	47.190478	-95.211350	-9.34	-73.92

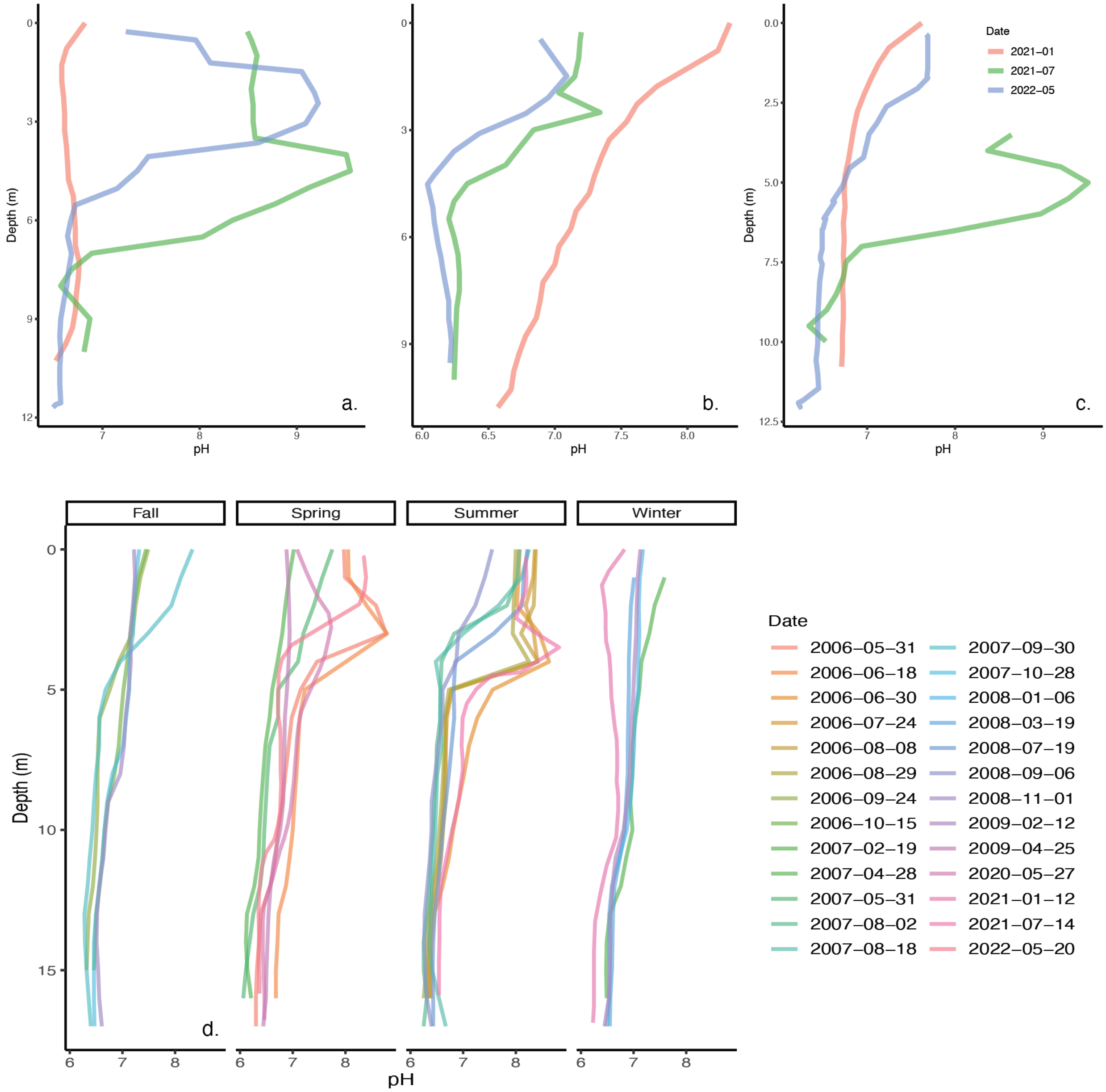
The combined uncertainty (analytical uncertainty and average correction factor) for $\delta^{18}O$ is ± 0.04‰ VSMOW) and $\delta^{2}H$ is ± 0.25‰ (VSMOW), respectively.



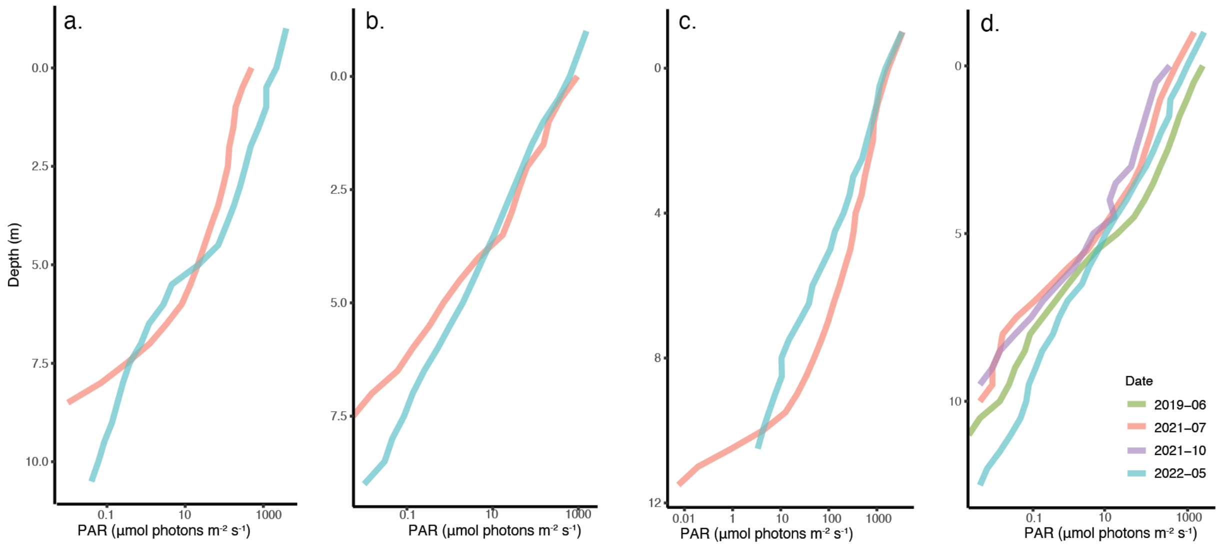
Supplementary Figure 16. The range of $\delta^{18}O_{H2O}$ calculated for water vapor based on temperature records from the ITCM5 station calculated according to Engel & Magner, 2019.



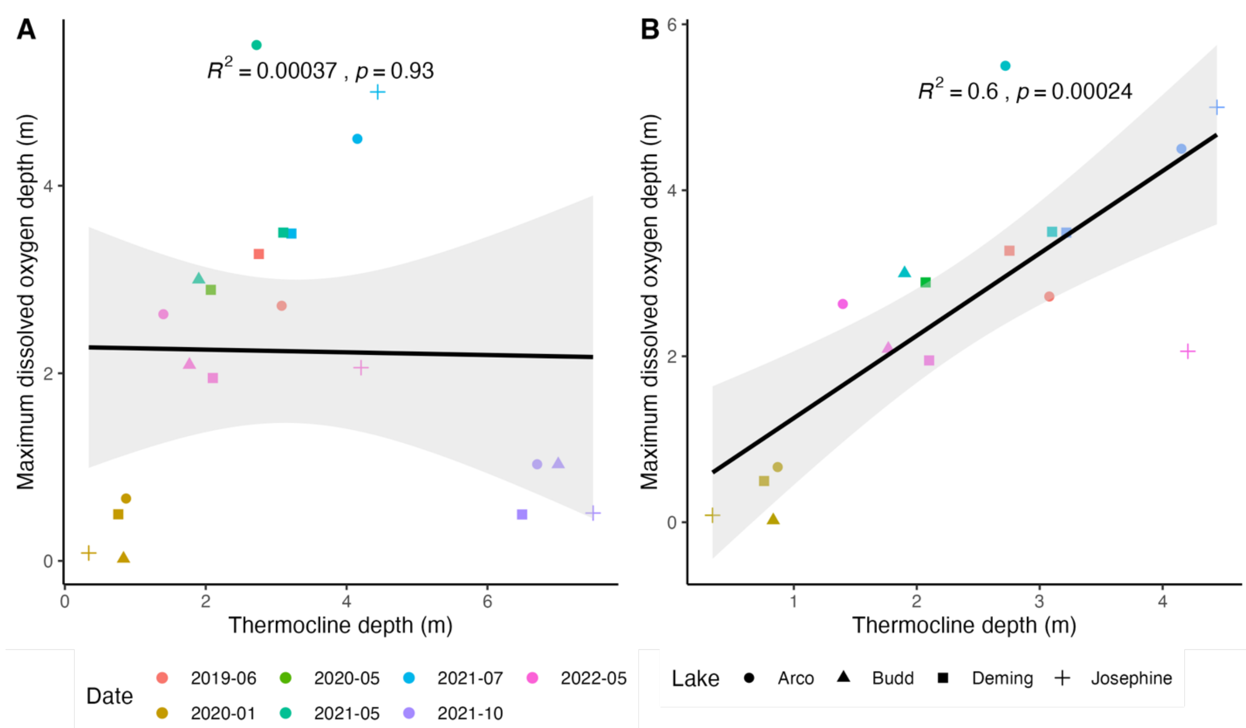
Supplementary Figure 17. Cyanobacteria (top row) and eukaryotic algae (bottom row) observed in the study lakes in May 2022.



Supplementary Figure 18. pH profiles of a) Arco Lake, b) Budd Lake, c) Josephine Lake, and d) Deming Lake. For Deming Lake, seasons were classified according to solstice and equinox dates.



Supplementary Figure 19. Photosynthetically active radiation (PAR) profiles of a) Arco Lake, b) Budd Lake, c) Josephine Lake, and d) Deming Lake.



Supplementary Figure 20. Co-variation between the thermocline depth and the depth of the maximum in dissolved oxygen, and the SCML. Panel A includes data from all dates, and panel B lacks data from October 2021. The correlation is significant when October 2021 datapoints are removed.