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Drivers of hydrologic budgets in small terminal lakes in the Alberta prairies

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ABSTRACT

The prairies and boreal plain within the North Saskatchewan Watershed (NSW) of Central Alberta have numerous shallow ponds and lakes that sustain unique aquatic ecosystems and are critical habitat for migratory waterfowl in North America. However, over the past 20 years water levels have declined and the reasons are unresolved. Here we used a combination of inorganic geochemical analyses and stable water isotopes to constrain the hydrologic budgets of six lakes in the NSW. Our results show that the bedrock groundwater major element geochemistry is controlled by chemical weathering reactions along the flow paths and is dominated by lower $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values (i.e. isotopically depleted), while the lake water generally shows unchanging evaporatively enriched stable isotope values and cation concentrations. An isotopic mass balance (IMB) technique combined with solution geochemical modelling using activity – activity plots reveals that deep groundwater input is negligible, while the lakes appear to lose a greater fraction of water inflows to evaporation (60%) than shallow groundwater and surface outflow (40%). The relative importance of shallow groundwater requires further study, as shallow groundwater sampling locations are scarce and surface outflow is negligible. The IMB technique also indicated that these prairie lakes have short water residence times, ranging from 1.8 to 10.4 yrs. Our results suggest that declining lake levels are likely the result of a changing relationship between precipitation and evaporation from the climatic norm.

RÉSUMÉ

Les prairies et la plaine boréale du bassin versant de la rivière Saskatchewan Nord (RSN) du centre de l'Alberta abritent de nombreux étangs, marres et lacs peu profonds qui soutiennent des écosystèmes aquatiques uniques et constituent un habitat essentiel pour les oiseaux migrateurs en Amérique du Nord. Cependant, au cours des 20 dernières années, les niveaux d'eau ont drastiquement diminué et les raisons environnementales restent inexplicables. Cette étude utilise une combinaison d'analyses géochimiques inorganiques et isotopiques de l'eau pour contraindre les bilans hydrologiques de six lacs de la RSN. Nos résultats démontrent que les éléments majeurs des eaux souterraines sont contrôlés par des réactions liées à l'altération chimique sur les zones d'écoulements et sont dominés par des valeurs $\delta^{18}\text{O}$ and $\delta^2\text{H}$ plus basses (c'est-à-dire isotopiquement appauvries). Au contraire, l'eau des lacs montre généralement des valeurs isotopiques stables enrichies par l'évaporation et des concentrations constantes en cations. Une technique de bilan isotopique (IMB), combinée à la modélisation géochimique des solutions et des graphiques d'activité révèle que l'apport en eaux souterraines profondes est négligeable. En revanche, les lacs semblent perdre leur plus grande fraction des apports en eau par évaporation (60%), puis par les eaux souterraines peu profondes et les écoulements de surface (40%). L'importance relative des eaux souterraines peu profondes nécessite des études supplémentaires, car les emplacements d'échantillonnage des eaux souterraines peu profondes sont rares et les écoulements de surface sont négligeables. La technique IMB a également indiqué que les lacs de prairies étudiés ont des temps de résidence courts, variant de 1,8 à 10,4 années. Nos résultats suggèrent que la diminution des niveaux des lacs est probablement le résultat d'une évolution de la relation entre les précipitations et l'évaporation par rapport à la norme climatique.

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Groundwater; hydrologic budgets; environmental geochemistry

Introduction

Many small prairie lakes in western Canada have experienced a decline in water levels for the past three decades (van der Kamp, Keir, and Evans 2008; North Saskatchewan Watershed Alliance (NSWA) 2017). In drought-prone areas of Alberta, declining water levels have occurred in the context of an increase in mean annual temperature of 1.6 °C over the past century (Bonsal et al. 2013; Sauchyn and Kulshreshtha 2008). While some of these lakes have begun to recover in recent years, many remain below the historical average (~50% within the North Saskatchewan watershed) at the time of this study between April 2016 – September 2017 (North Saskatchewan Watershed Alliance (NSWA) 2017). Understanding the relationship between a changing climate and small prairie lakes is important, as it is generally accepted that precipitation is the primary input to the hydrologic budget of most wetlands and lakes in Alberta (Carey et al. 2010; Carrera-Hernandez et al. 2012; Mwale et al. 2009; Redding and Devito 2008; Smerdon, Mendoza, and Devito 2008). However, the relative contribution of groundwater to the hydrologic budgets of Alberta's prairie lakes is uncertain, with some literature arguing for substantial groundwater input and others arguing that the budgets are dominated by precipitation and evaporation (van der Kamp, Keir, and Evans 2008; Carrera-Hernandez et al. 2012; Gibson et al. 2016b; Hickman 1974; Redding and Devito 2008; Schwartz and Gallup 1978; Thompson et al. 2015).

Historically, lake hydrologic budgets have been based on parameters derived from climate monitoring, such as precipitation and evaporation. These approaches have been supplanted by stable water isotopes and quantitative lake isotope theory (Gibson, Birks, and Yi 2016a). The stable isotope approach has been successfully applied to determine lake water budgets in numerous studies when incorporated with the evaporation term (e.g. Gibson, Prepas, and McEachern 2002; Jones and Imbers 2010; Prepas et al. 2001; van der Kamp, Keir, and Evans 2008). Isotope-based approaches to lake hydrological budgets take advantage of the preferential evaporation of lighter stable isotopes of hydrogen and oxygen, causing the enrichment of heavier isotopes in lakes that can provide estimates of evaporation, mixing, and groundwater input into them (Craig 1961; Gibson et al. 1993). The isotopic mass balance (IMB) approach was developed for specific lacustrine systems, such as small lakes with varying degrees of outflow. IMB calculations are more successful when applied to

relatively simple, well mixed systems that can be modelled under the assumption of consistent water density and steady state behaviour (i.e. the sum of inflow and precipitation is equal to the sum of outflow and evaporation) (Gibson, Prepas, and McEachern 2002; Gibson et al. 2016b).

The use of aqueous geochemistry as a means of determining hydrologic budgets, although less prevalent than stable isotopic analyses, has historically provided insight into groundwater residence times, flow paths (Tóth 1963; Tóth 1999), and interaction with lakes (Rosenberry et al. 2015). In this regard, inorganic chemical mass balance calculations have been conducted by quantifying the major ions of the system, such as Na^+ , K^+ , Mg^{2+} , Ca^{2+} , Cl^- , HCO_3^- , CO_3^{2-} , and SO_4^{2-} (Mitchell and Prepas 1990; Schwartz and Gallup 1978). The methods of using major ions to determine the roles of components in hydrologic systems vary widely, including time series plots of ion concentrations (Schwartz and Gallup 1978), ternary diagrams (Grasby, Hutcheon, and McFarland 1999; Marini et al. 2000), Piper diagrams (Rodriguez-Rodriguez et al. 2006), and the comparison of relative proportions of major ions (LaBaugh et al. 1997). More recently, traditional chemical mass balance techniques have been coupled to thermodynamic calculations in the form of activity – activity plots (Banoeng-Yakubo et al. 2009; Bruni et al. 2002; Grasby, Hutcheon, and McFarland 1999; Marini et al. 2000).

Despite the respective advantages of the IMB and chemical mass balance approaches, the techniques are seldom used in combination to determine hydrologic budgets for lakes. Here we use a combination of stable water isotopic measurements, inorganic chemical mass balances, and activity – activity plots to assess the hydrologic budgets of six prairie lakes that have experienced decadal declines in water levels. Together, these techniques demonstrate that water provenance and hydrologic budgets can be learned using relatively straightforward field sampling and laboratory analyses.

Physical setting

The North Saskatchewan River Watershed (NSW) spans approximately 57,000 km² in Alberta and Saskatchewan, Canada. The NSW is subdivided into 12 tributary watersheds, of which the area of study spans two, the Modeste and Sturgeon (Figure 1), located about 50 km west of Edmonton, Alberta. The Modeste watershed includes small wetlands and lakes, including four of the lakes in this study, and is

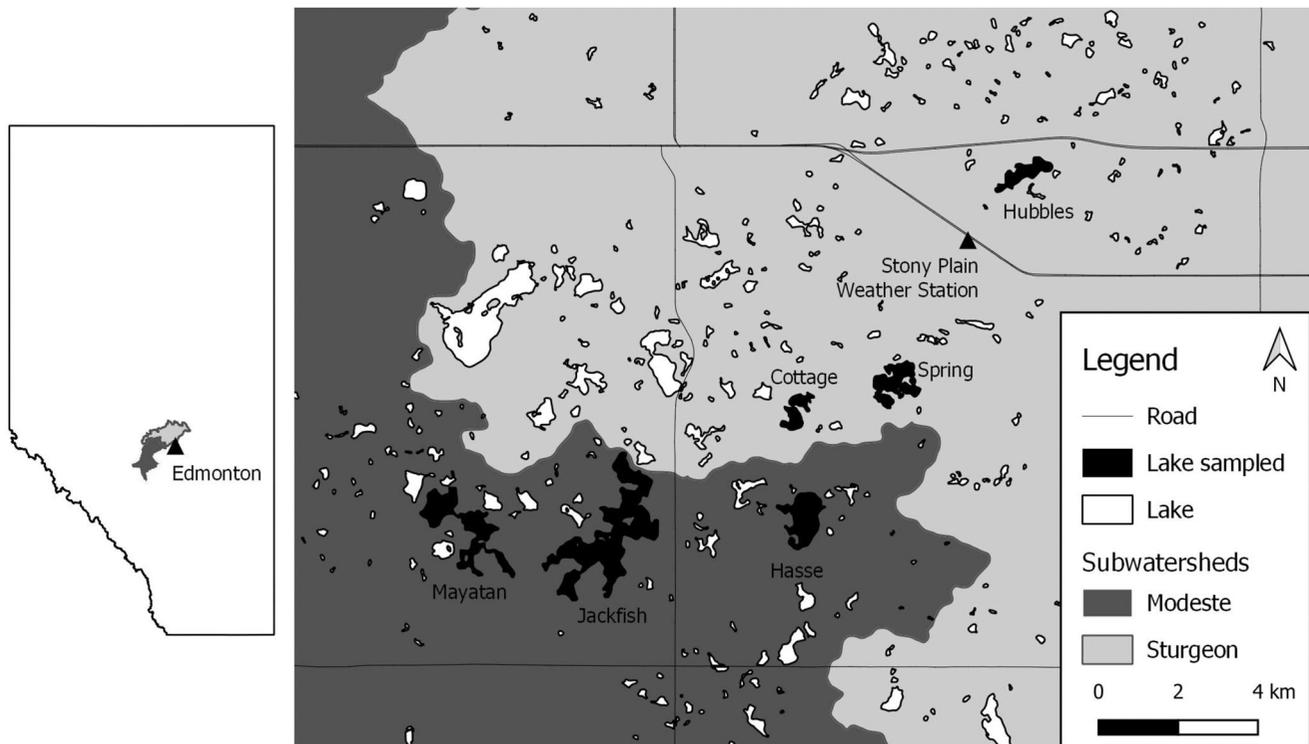


Figure 1. A map of the lakes study area: Cottage Lake, Hasse Lake, Hubbles Lake, Jackfish Lake, Mayatan Lake, and Spring Lake and their location within Alberta. Weather data was collected from Stony Plain weather station. Source: Map was made using ArcGIS.

bordered to the north by the Sturgeon watershed. The Sturgeon watershed includes the community of Spruce Grove and several smaller lakes including two lakes in this study (North Saskatchewan Watershed Alliance (NSWA)), 2007). For three of the lakes studied, the North Saskatchewan Watershed Alliance (NSWA) has summarized the background physical and biological characteristics available from government studies and scientific research to support watershed management planning (North Saskatchewan Watershed Alliance (NSWA)) 2012, 2016, 2018).

Geologically, the uppermost bedrock unit is the Cretaceous Horseshoe Canyon Formation (Prior et al. 2013) that consists of coal, shale and sandstone units. The sandstones and fractured coal seams represent the primary sources of groundwater and are targeted for residential water supply in the study area. The unconsolidated sediments overlying Horseshoe Canyon Formation are primarily deposits from a pitted delta that formed during the last deglaciation, known as the Carvel Pitted Delta. The heterogeneous delta deposits consist of sand and silt, with some till and gravel (Andriashek, Fenton, and Root 1979) and vary from approximately 40 to 90 m thick (Hartman 2020). More broadly across the region there are more deeply incised bedrock channels containing pre-glacial

deposits; however, these are not present directly beneath the study area. The six lakes evaluated in this study are associated with depressions in the pitted delta (i.e. kettle lakes). The pitted delta deposit represents a present-day upland, and regional groundwater recharge zone (HCL (Hydrogeological Consultants Ltd.) 1998).

The primary water uses in the area are agricultural and residential, although there are a variety of recreational uses as well (North Saskatchewan Watershed Alliance (NSWA)) 2016). With a growing population proximal to many of the lakes, water usage in the study area has increased although exact water usage numbers are unknown (North Saskatchewan Watershed Alliance (NSWA)) 2013, 2016). In recent years, residents have observed a notable decline in water levels at lakes within the study area, leading to concerns about water use and sustainability. Concerns about lake level declines are confirmed by studies reporting lowering water elevations and decreased storage per year compared with historical averages with approximately 50% of the lakes in the North Saskatchewan watershed showing below normal or much below normal water levels as of 2015, an increase from ~25% in 2000 (North Saskatchewan Watershed Alliance (NSWA)) 2016, 2017). In this

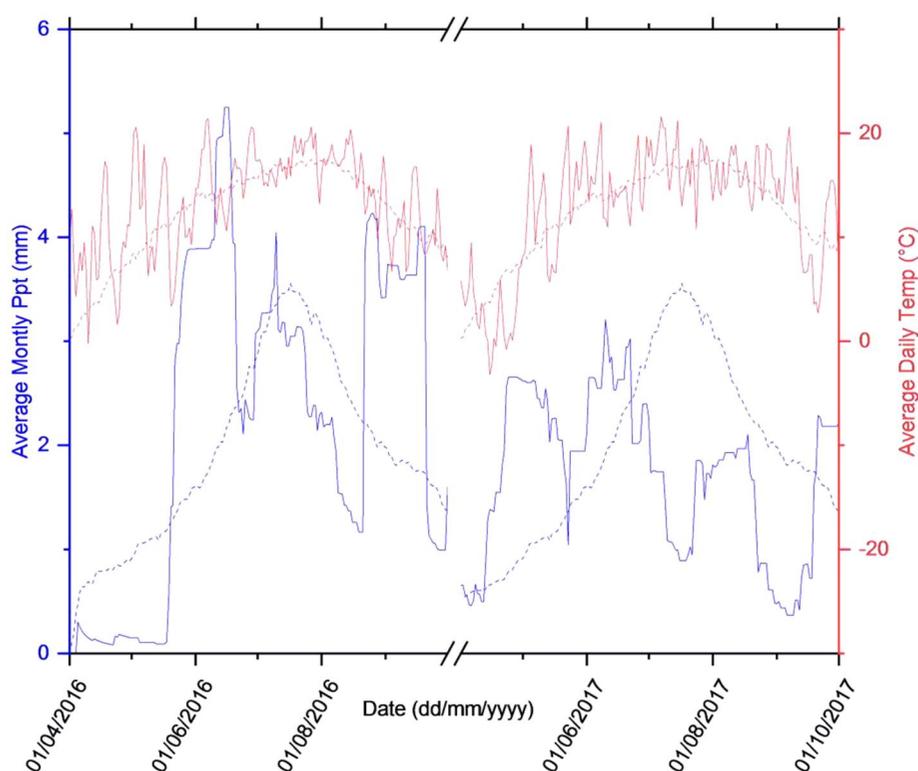


Figure 2. Average monthly precipitation (blue) and average daily temperature (red) data for April 1, 2016 to October 1, 2017, compared with historical averages of 1961 – 2018 from the Stony Plain weather station retrieved from Alberta agriculture and forestry database (dashed lines).

study, we aim to determine components of the hydro-logic budget for several lakes as a means to understand the declining water levels and the implications for future lake levels in the area.

The weather during the period of the study, April 2016 – September 2017, was characterized by normal precipitation and mean daily air temperature when compared to the 1961–2018 mean for the area (Figure 2; Edmonton Stony Plain weather station, ID 30122 F). Regional evaporation estimates for the area were obtained from two sources: surface evaporation from the North American Regional Reanalysis (NARR; Mesinger et al. 2006), and shallow lake evaporation (SLE) mapping in Alberta (Alberta Environment and Sustainable Resource Development (AESRD) 2013) using Morton’s (1983) method. Both methods provide regional estimates of evaporation data, and do not represent direct measurements from lakes themselves, which were unavailable for the lakes of this study. While this approach does introduce increased error due to the potential oasis effect of lakes, it has been determined that using regional estimates is sufficient for the purposes of this study, as the lakes are shallow (Morton 1983) and therefore we find this to be a valid method for our IMB approach.

The mean annual temperature of the study area has been relatively stable over the last 20 years, with year-to-year fluctuations. However, since 1880 the mean annual temperature has risen by 2.7°C (Anis et al. 2021a) and is projected to rise an additional 2°C by 2050 (Anis et al. 2021a).

Methods

Samples were collected from six lakes within Parkland County: Cottage Lake, Hasse Lake, Hubbles Lake, Jackfish Lake, Mayatan Lake, and Spring Lake (Figure 1), as well as residential wells and rainwater collectors. Most of the lakes in this study are relatively small terminal lakes (<1.5 km²) fringed by small residential developments. These lakes were selected as part of an outreach program led by the North Saskatchewan Watershed Alliance (NSWA), in response to the declining water levels in the area (North Saskatchewan Watershed Alliance (NSWA), 2017). Based on previous measurement of water temperature and dissolved oxygen profiles for Mayatan Lake (North Saskatchewan Watershed Alliance (NSWA)) 2012), Jackfish Lake (North Saskatchewan Watershed Alliance (NSWA)) 2016), and Hubbles

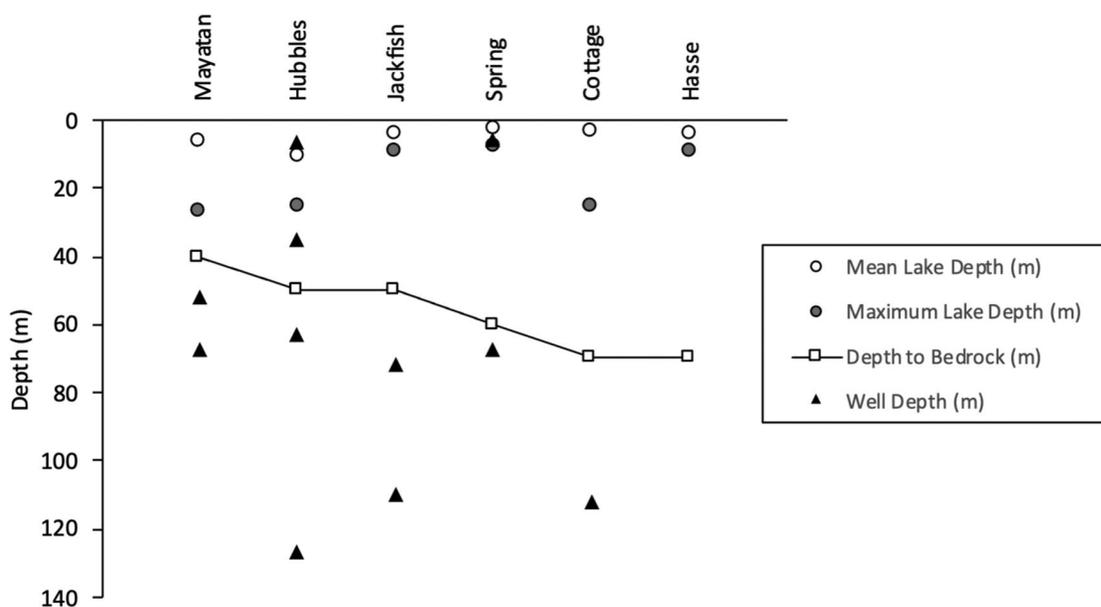


Figure 3. Mean and maximum depths of each lake compared to the depths of residential wells and the top of bedrock.

Lake (North Saskatchewan Watershed Alliance (NSWA) 2018), vertical mixing occurs at least intermittently, or more frequently where the lakes are shallow. While it is possible that the deepest portions of some lakes may not fully mix every year, we assume that there is sufficient mixing to justify the IMB approach. Most of the water sampling was conducted by local volunteers, with a portion of the sampling campaign conducted by researchers in June of 2017 for comparison with the volunteer-collected samples. Volunteer sampling was generally performed weekly during the summer of 2016 and biweekly during the summer of 2017. In total, water samples were collected from 15 locations at the lakes (varying from 1 to 4 locations on each lake depending on distribution of the resident volunteers) and 11 residential wells (varying in depth from 6 to 126 m). The depths of each lake and residential well are shown in Figure 3 with the depth to the bedrock underlying the delta deposits. Drilling records indicate that most residential wells are completed within sandstone units in the Horseshoe Canyon Formation, often about 10 m below the contact between the overlying sediments and the bedrock.

Water samples were collected into 50 mL polypropylene tubes with screw cap lids (Corning™ Falcon™ 50 mL Conical centrifuge tubes) filled to the top, with as little head space as possible and refrigerated at 4 °C until analysis at the University of Alberta. In the laboratory, samples were subdivided into aliquots for water stable isotope analysis and metals analysis. The aliquots for metals analysis were filtered using 0.2 µm nylon membranes and acidified at the

time of subdivision with 6 µL of 70% American Chemical Society grade nitric acid, approximately 48 h after collection. To assess the reliability of samples collected by the volunteers and to collect more data parameters, a representative sampling of the study area was conducted by members of the research team in June of 2017. During this sampling, more field parameters were measured using a field water-chemistry probe, including electrical conductivity (EC), temperature, and pH. For the representative sampling in 2017, four samples were taken at each sampling site at approximately 30 cm depth. The samples were as follows: an acidified and filtered (0.2 µm nylon membranes) 15 mL sample for metals analysis; an unfiltered 15 mL sample collected with zero headspace for alkalinity analysis; a filtered (0.2 µm nylon membranes) 50 mL sample for anion analysis; and a 50 mL sample for stable water isotope analysis and as a reserve for additional testing as necessary.

Within 48 h of sampling, alkalinity titrations were performed using a Metrohm Titrando 905 autotitrator. Cation and anion concentrations, as well as stable water isotope analyses, were completed within a week of sampling. The representative sampling showed that data collected for researcher-collected samples agreed with those collected by volunteers, with differences in measured concentrations <5% for all major cations (Ca^{2+} , Mg^{2+} , K^+ , Na^+). Samples were analysed on a triple quadrupole inductively coupled plasma mass spectrometer (ICP-MS/MS; Agilent 8800) for metals, an ion chromatograph (IC; Dionex DX 600) for anions, and a Picarro Cavity Ring-Down Spectroscopy L2130-i Isotopic Water Analyzer for stable water

isotopes. During ICP-MS/MS analysis, indium was used as an internal calibration standard to correct instrumentation drift and repeated measurement of internal laboratory standards using certified concentrations to quantify the analytical reproducibility. Standards made from refrigerated 1000 mg/L certified ICP-MS/MS standard stock solutions covered a range of 0.001 to 30 mg/L in two tiers to account for varying concentrations in the samples. Samples were analyzed directly or diluted 10x prior to analysis to ensure values fit within the acceptable range of the calibration curve. The calibration curve was measured every 30-40 samples. As needed, various gas-modes, including H₂, O₂, He, and no gas, were used to reduce isobaric interferences. All values are reported in SI-1. For IC, certified external reference solutions were used to calibrate the instrument so that measurements had an error less than ±5%. During stable water isotopic measurements, two international standards, USGS 45 and 46, and internal laboratory created standards, Evian and QCDI, during each analysis, were measured. The Picarro Isotopic Water Analyzer undertakes eight injections per sample, the last four of which are adopted in result calibration by a software. Based on repeated measurements of lab standards, analytical uncertainties of the Picarro L2130-i are 0.2‰ and 0.6‰ for δ¹⁸O and δ²H respectively.

Thermodynamics calculations

Activity – activity plots were constructed in order to evaluate the relationship between the groundwater and lake water, using the method of Grasby, Hutcheon, and McFarland (1999). These plots are based on the premise that ion exchange reactions that occur in the interlayers of clays, such as smectite, between Na⁺, and Ca²⁺ and Mg²⁺, control the major ion geochemistry of shallow groundwater and surface water (Grasby, Hutcheon, and McFarland 1999). Prior to plotting, the activities of the major cations (K⁺, Na⁺, Ca²⁺, Mg²⁺) were normalized by pH by dividing by the activity of the ions by the activity of the H⁺ ions calculated from the pH measurements taken at the time of collection (SI-2). Ion activity coefficients, γ_i, were calculated using the Debye – Hückel equation (see SI-3 for more information). Gibbs energies of reaction (Δ_rG) were calculated for the reaction boundaries using standard Gibbs energy of formation (Δ_fG°) values for clays and minerals (Abercrombie 1988; Anderson 1996; Woods and Garrels 1987). Because phase boundaries are temperature-dependent, they were calculated over a range of temperatures

(10 °C, 15 °C, 20 °C, and 25 °C) for each activity – activity plot, using the van't Hoff equation to adjust ΔG values for temperature (Figure 4, SI-3).

Stable isotope calculations

In lacustrine settings, changes in stable water isotopes are driven primarily by ambient temperature influences, calculated based on the temperature dependent isotopic fractionation coefficient (Gibson, Birks, and Yi 2016a). Additionally, deuterium excess, defined as:

$$d = \delta^2\text{H} - 8 \delta^{18}\text{O} (\text{‰}) \quad (1)$$

where δ²H and δ¹⁸O denote the deuterium and oxygen-18 abundance relative to Vienna Standard Mean Ocean Water (VSMOW), was also calculated to evaluate evaporative influences on the surface water of each lake (Pfahl and Sodemann 2014). Similar to the approach of Gibson, Prepas, and McEachern (2002) and Gibson et al. (2016b), the IMB approach is used here to systematically estimate lake throughflow and residency for samples collected in 2016 and 2017. We follow the approach described by Gibson, Birks, and Yi (2016a, Gibson et al. 2016b) to estimate the throughflow index (i.e. evaporation/inflow ratio) that describes the fraction of total water inflows that are lost by evaporation, which in-turn can be used to estimate the residence time of water in a lake. The equations, terms, and data sources are provided in SI-5 with an example for one of the lakes. We used average values for the period of sampling (2016 to 2017) for the isotopic composition of each lake and precipitation (measured in this study), and air temperature and relative humidity (obtained from the Edmonton Stony Plain weather station shown in Figure 1). To calculate the isotope-based water residence time, lake attributes (area, volume) were obtained from the Atlas of Alberta lakes (Mitchell and Prepas 1990) and the NSWA, and two values of annual depth-equivalent evaporation were obtained from NARR (Mesinger et al. 2006) and the Alberta Government (Alberta Environment and Sustainable Resource Development (AESRD) 2013). The NARR evaporation represents surface evaporation, and the Alberta Government uses Morton (1983) to estimate shallow lake evaporation (SLE). Both evaporation values represent an area large enough to encompass all of the lakes in this study.

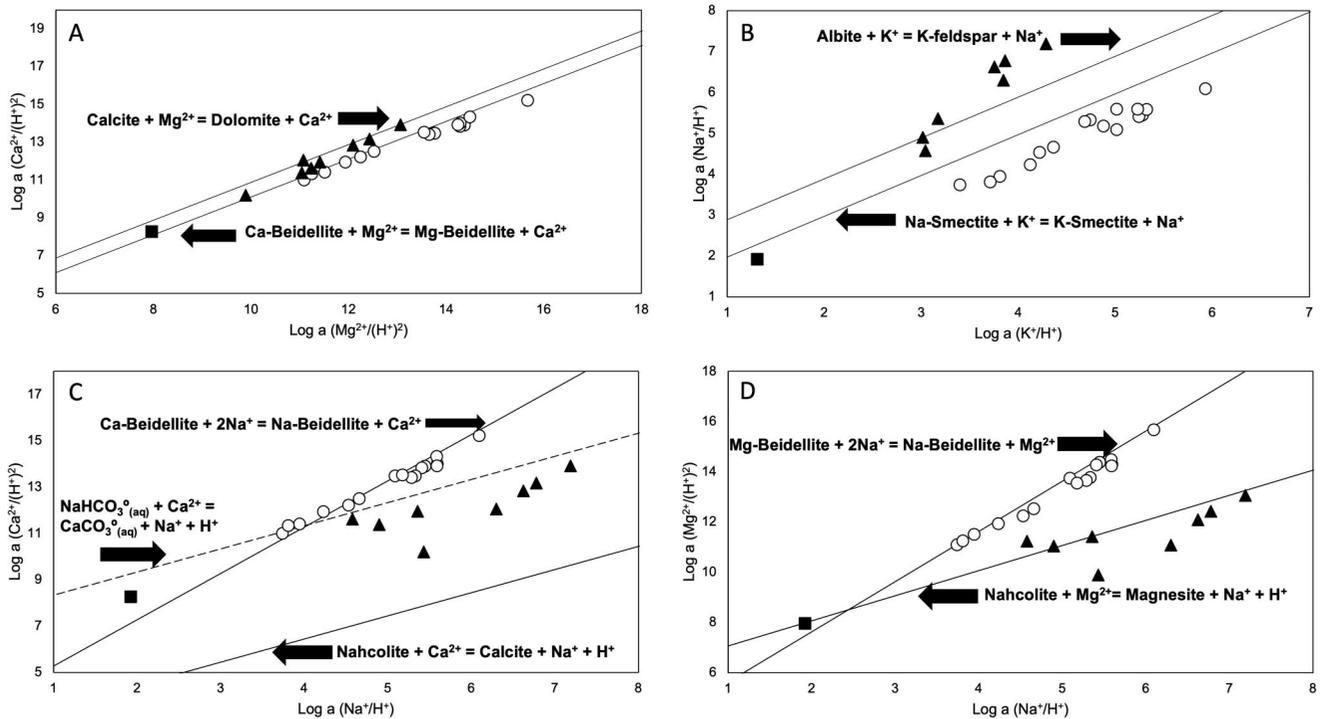


Figure 4. Activity – activity plots of lake water (white circles) and groundwater (black triangles). a shallow groundwater sample, located near Spring lake with potential groundwater/lake water interaction, is reported as a black square. Phase boundaries were calculated at 1 bar and 15 °C and show relationships between A) $\log a \text{ Mg}^{2+}/(\text{H}^+)^2$ vs. $\log a \text{ Ca}^{2+}/(\text{H}^+)^2$, B) $\log a \text{ K}^+/\text{H}^+$ vs. $\log a \text{ Na}^+/\text{H}^+$, C) $\log a \text{ Na}^+/\text{H}^+$ vs. $\log a \text{ Ca}^{2+}/(\text{H}^+)^2$, and D) $\log a \text{ Na}^+/\text{H}^+$ vs. $\log a \text{ Mg}^{2+}/(\text{H}^+)^2$.

Results and discussion

Inorganic chemical relationship between groundwater and lake water

Using a modified method based on Grasby, Hutcheon, and McFarland (1999) the relationships between Na^+ , Mg^{2+} , K^+ and Ca^{2+} at 15 °C are shown in Figure 4. The clay minerals that were chosen for activity – activity calculations (i.e. beidellite and smectite) were based on the reasoning of Grasby, Hutcheon, and McFarland (1999): (1) that the thermodynamic parameters required for the phase boundary calculations were available, and (2) that the minerals are represented in Alberta's geologic setting. Phase boundaries were calculated and displayed over the range of temperatures measured for all samples (see supplemental plots at 10, 20, and 25 °C), although no significant change was observed over the 10 °C to 25 °C temperature range. In all four plots, the lake water falls along the smectite group clay mineral phase boundary, while the groundwater plots along the primary mineral phase boundary, either carbonate (i.e. calcite – dolomite, nahcolite – calcite, nahcolite – magnesite) or silicate (i.e. albite – K-feldspar). In all cases the phase boundaries represent cation exchange reactions between two minerals, and although the minerals selected may not be the precise

or only minerals present, the method of Grasby, Hutcheon, and McFarland (1999) serves the purpose of differentiating groundwater from lake water.

The activity – activity plots reveal little to no overlap between the groundwater in the bedrock and surface water inorganic chemical reactions, indicating there is little interaction between the lake and bedrock groundwater. The exceptions are a few shallow groundwater samples (<6 m) where the activities plot at points of intersecting phase boundaries (Figure 4). This result appears to contrast previous literature on prairie lakes (Crow and Schwartz 1985; Schwartz and Gallup 1978), which focused on major ion chemistry (Na^+ , K^+ , Mg^{2+} , Ca^{2+} , Cl^- , HCO_3^- , CO_3^{2-} , and SO_4^{2-}) to argue that groundwater is the dominant contributor to the water chemistry of the lakes. Often these previous studies found similar concentrations between the lake water and runoff, ice, and groundwater. However, by accounting for pH and ionic strength variations and temperature, we show that absolute ion concentrations of the lake may only be similar to shallow groundwater, and that the bedrock groundwater sources are not comparable.

Further evidence to illustrate a disconnected chemical relationship between the lake water and the measured groundwater is provided by thermodynamic calculations, with groundwater at chemical equilibrium with different

phases than the lake water (Figure 4). This indicates there is little to no bedrock groundwater input into the lake, as both the bedrock groundwater and lake water would be at chemical equilibrium with the same phases if there was substantial groundwater input from the measured wells. For example, Figure 4a shows bedrock groundwater to be in equilibrium between calcite and dolomite, while the lake water samples are in equilibrium between Ca- and Mg-rich beidellite. Carbonate aqueous species are implicit in the equations outlined in Figure 4a, through the dissolution of calcite and dolomite. Although the CO_3^{2-} aqueous species is not given explicitly in the final balanced equation between calcite and dolomite, it is present in the two reactions that were summed to give the calcite-dolomite reaction. These thermodynamic calculations indicate that groundwater input is restricted to shallow groundwater, < 6 m below ground level in most cases. The findings presented here are in agreement with more recent literature that, although not focused on the Alberta prairies, suggest that many prairie lakes across Canada and the United States are closed basins with minimal groundwater input (e.g. LaBaugh et al. 1997; van der Kamp, Keir, and Evans 2008, Xiao et al. 2018).

Piper diagrams

The relationships between the lakes and their respective groundwaters were determined using Piper diagrams. They show the composition of the lakes by the percentage of each major ion, rather than by their concentration, to eliminate the dilution effect. The data from the 2017 season are presented here, which contain alkalinity and anion data, while the more extensive 2016 data are shown in a cation ternary diagram, because alkalinity and anion measurements were not made in 2016 (Figure 5).

The Piper diagrams also illustrate that there is little connection between the measured bedrock groundwater and surface water, showing overlap only in shallow groundwater well samples (Figure 6). They also reveal relatively large differences in chemical composition among the lake water samples, likely due to the underlying lake sediments. Variations in anion chemistry are the product of variations in the dissolved inorganic carbon, primarily HCO_3^- and CO_3^{2-} , which varied considerably (with levels between 113-972 ppm and 0.4-15.7 ppm, respectively) (SI-1). It is also possible that this pronounced difference between lake water and groundwater is also due to elevated sulphate concentrations in the lake water due to sulphate leaching of glacial till during spring runoff. In all cases the proportional and absolute chloride

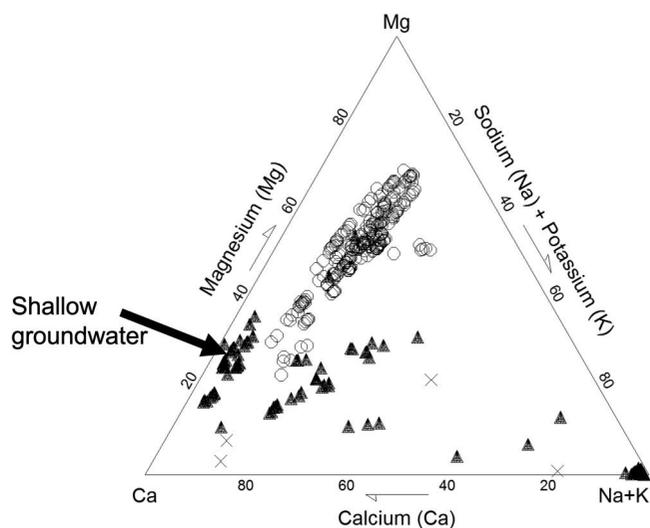


Figure 5. Cation ternary diagram samples collected in the summer of 2016. Lake water is depicted in circles, groundwater in triangles and rain water in \times . Shallow groundwater is indicated with an arrow.

concentrations were low in regional groundwater and lake water.

Although the Piper diagrams do not reveal spatial or temporal trends among the lakes, they do reveal separate groupings of bedrock groundwater and lake water. This is because bedrock groundwater has higher proportions of sodium and bicarbonate (approximately 71% and 85% of total cations and anions respectively), which is consistent with regional groundwater chemistry mapping (Barker et al. 2013). The shallow groundwater again appears to be an exception, which is more balanced in its cation composition (with average compositions of Ca, Mg, Na, and K of 65%, 18%, 3%, and 1%, respectively), lies closer to the lake water (38%, 36%, 14%, and 12%, for Ca, Mg, Na, and K, respectively), and plot near the centre of the cation ternary diagram. The groundwater was found to become steadily more Na-rich with increasing well depth revealing a depth-driven cation exchange reaction with Ca^{2+} occurring in the groundwater, a known common occurrence in groundwater chemistry (Tóth 1963). This trend in depth-driven cation exchange reaction occurs in the residential wells around each lake, but appears to occur at differing rates at each lake, possibly indicating variations in the sediment thickness above bedrock, and the associated difference between these groundwater sources.

Stable water isotopes

The isotopic composition of the lakes in the study region indicates higher $\delta^{18}\text{O}$ values ($\delta^{18}\text{O} \sim -5\text{‰}$ to -9‰) consistent with other studies of lakes in the

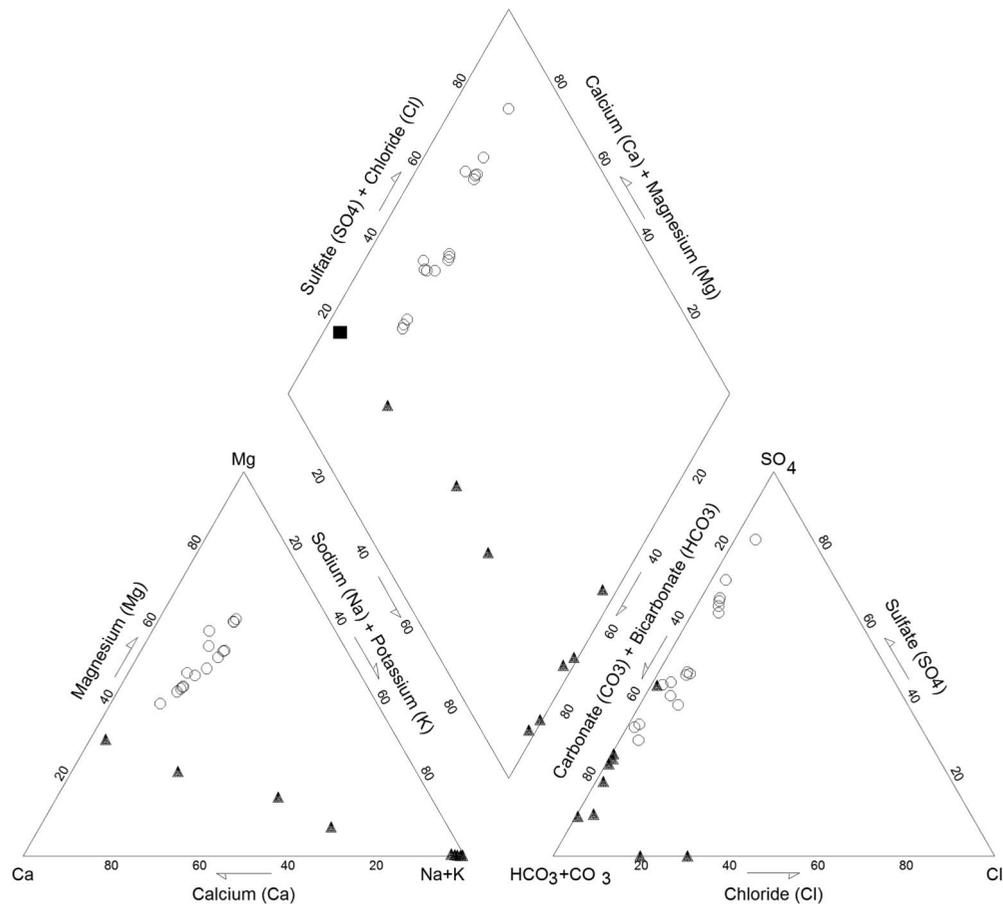


Figure 6. Piper diagram plot of samples collected in 2017, illustrating trends among lake water and groundwater. Triangles indicate surrounding lake well water samples, squares indicate shallow groundwater, and circles indicate lake water samples.

region (Gibson et al. 2016b; Prepas et al. 2001; van der Kamp 2008), while the bedrock groundwater has lower values ($\delta^{18}\text{O} \sim -11\text{‰}$ to -19‰) (Figure 7, SI-4). The nearly weekly sampling across the 2016 season and subsequent sampling in 2017 revealed minimal variation in isotopic composition. There were minor variations observed in specific samples because of precipitation events; however, the time series results (Figure 7, SI-4) demonstrate remarkably constant isotopic values in samples at all locations. Small lakes on the prairie landscape are generally expected to be influenced by freshwater from spring snowmelt, resulting in water with a lower $\delta^{18}\text{O}$ value. Similarly, we would expect the isotopic composition of the lake water to have greater $\delta^{18}\text{O}$ values towards the end of the summer due to strong evaporative effects; however, neither of these effects were observed. The lack of seasonal variation in isotopic composition across the 2016 and 2017 sampling periods from the spring ice thaw to fall freeze up again suggests that the water budgets of these lakes are minimally affected by seasonal fluctuations and are more likely driven by long-term decadal cycling trends, which can be on the order of 50 years or more (van der Kamp,

Keir, and Evans 2008). In other words, the isotopic composition indicates well-mixed water bodies that are influenced by long-term precipitation and evaporation trends, rather than seasonal variations in temperature, precipitation, and evaporation. Alternatively, it is possible that there are other inflows with similar isotopic composition as the lakes (e.g. shallow groundwater within the delta deposits).

Co-isotope plots

The stable isotope ratios of water are shown on Figure 8 relative to the global meteoric water line (GMWL) of $\delta^2\text{H} = 8\delta^{18}\text{O} + 10$ (Craig 1961) and a local meteoric water line (LMWL) of $\delta^2\text{H} = 6.8\delta^{18}\text{O} - 18.9$ developed for Edmonton, Alberta from precipitation collected between 2014 and 2016 (Chamzuk 2015, Zhang 2016). The average isotopic composition of precipitation collected during 2016 as part of our lake study is very similar to the LMWL. Because the Global Network of Isotopes in Precipitation (GNIP) only has measurements from 1961 to 1966 for Edmonton, Alberta (IAEA/WMO. 2023), we use the 2014 to 2016 average determined in this study.

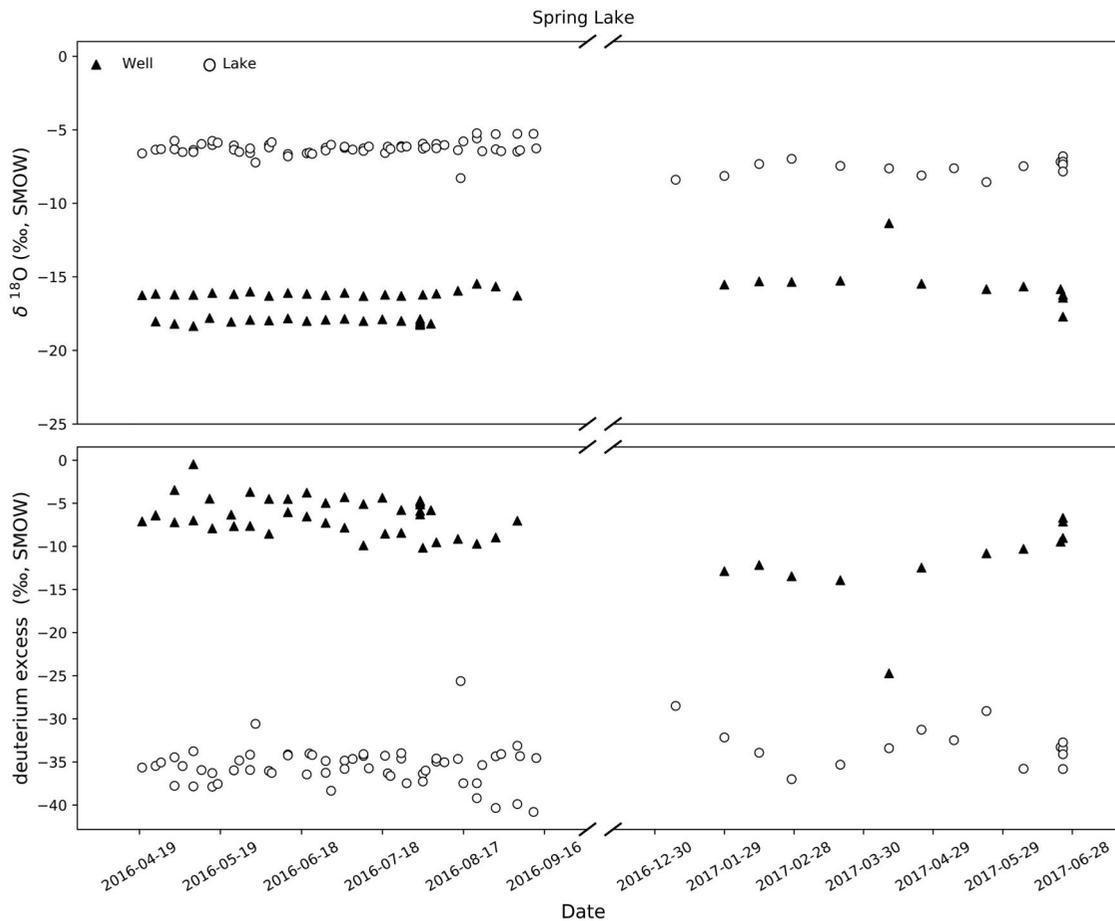


Figure 7. Stable water isotope plots for Spring Lake. Lake water data are plotted using circles, and surrounding groundwater with triangles, using both 2016 and 2017 data.

The local evaporation line (LEL) for the lake samples is $\delta^2\text{H} = 4.7\delta^{18}\text{O} - 56$, which is similar to the LEL of $\delta^2\text{H} = 5.3\delta^{18}\text{O} - 46.9$ reported by Gibson et al. (2016b) for a study of lakes across central Alberta, but including four lakes in the same region. For additional context, the results of the Gibson et al. (2016b) study are plotted on Figure 8, illustrating the slightly different LEL slopes, but general similarity in isotopic composition.

Three distinct water groups are apparent from the co-isotope plot (Figure 8): groundwater wells, groundwater wells near Mayatan Lake, and lake water. Within the group of lake water samples is also the result from a shallow residential well near Hubbles Lake (6 m depth). To investigate the relationship between isotopic composition of the lakes and groundwater collected from varying depths in the subsurface, a depth profile of $\delta^{18}\text{O}$ for the samples in and around Hubbles Lake is shown in Figure 9. Combined with the perspective of lake depth and depth to the bedrock, the $\delta^{18}\text{O}$ profile illustrates the evaporative enrichment experienced by the lake and shallow groundwater leading to higher $\delta^{18}\text{O}$ values, compared with the lower values at depth. This finding

aligns with the inorganic chemistry (i.e. activity – activity plots; Piper diagram), in that the lake water has a similar composition as shallow groundwater yet different than bedrock groundwater. The other locations with residential wells near lakes appear to have the same trend of lower isotopic values in bedrock groundwater. The exception to this was the Mayatan Lake well samples, which have isotopic values that lie between the lake water samples and the rest of the groundwater samples (Figure 7) despite the fact that they are from wells that are at 51.8 m and 67.1 m depth. Interestingly at this location, the depth to bedrock is the least of all locations (approximately 40 m) and the maximum depth of Mayatan Lake is 27 m, suggesting that evaporative enrichment in the shallow groundwater may be circulating to the upper part of the bedrock.

Isotope mass balance model

The IMB calculations determined that the throughflow index (i.e. evaporation/inflow ratio) is between 0.597 and 0.814 (Table 1), with most lakes in our study having a value of about 0.6. This range in values is similar to

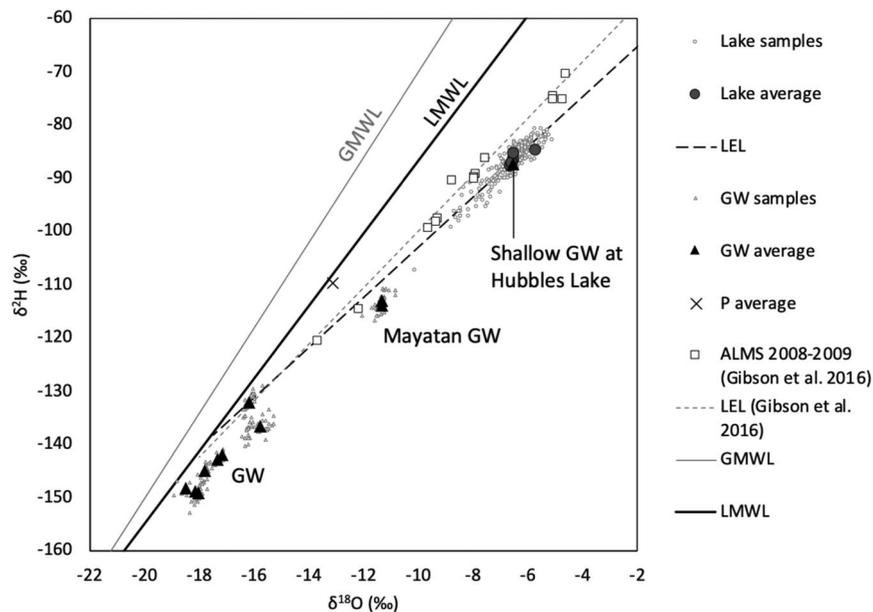


Figure 8. Co-isotope plot illustrating the global meteoric water line (GMWL), local meteoric water line (LMWL) for Edmonton, average precipitation for samples collected in 2016, and the groundwater and lake water individual samples and average value of each lake and groundwater well for the 2016–2017 period of sampling. The results of Gibson et al. (2016b) are shown for comparison.

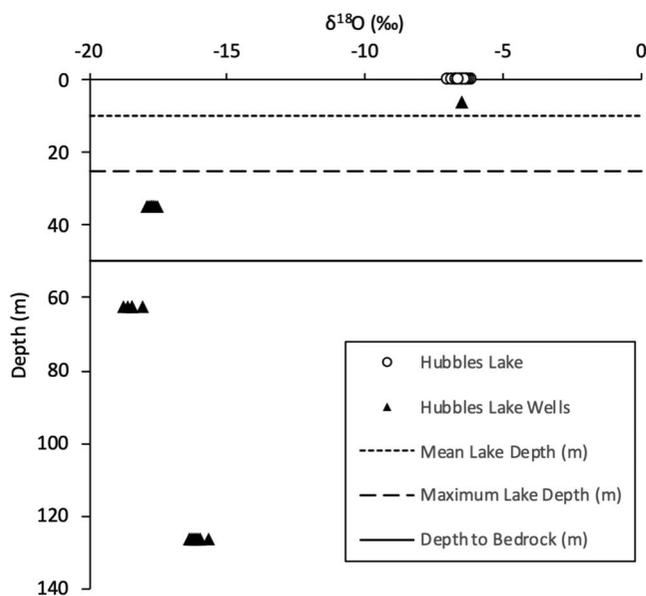


Figure 9. $\delta^{18}\text{O}$ depth profile for water samples collected at Hubbles Lake.

those estimated by Gibson et al. (2016b) for other larger lakes in central Alberta having a similar $\delta^{18}\text{O}$ value, as well as lakes in northeastern Alberta that had low runoff (Bennett, Gibson, and McEachern 2008). A throughflow index of 0.6 indicates that 60% of total water inflows to a lake are lost to evaporation, and that 40% could be lost to other processes such as surface outflow or groundwater recharge. Considering that the watershed summary reports for Mayatan Lake (North Saskatchewan Watershed Alliance (NSWA) 2012), Jackfish Lake

(North Saskatchewan Watershed Alliance (NSWA) 2016), and Hubbles Lake (North Saskatchewan Watershed Alliance (NSWA) 2018) indicate no surface outflow, it is likely that groundwater recharge processes could be responsible for much of the remaining outflows. Given the difference in isotopic composition between the lakes and bedrock groundwater samples, we suggest that net groundwater recharge from the lakes may remain in the shallow portion of the groundwater system.

A subsequent IMB calculation following the method outlined in Gibson, Birks, and Yi (2016a) identified the isotope-based water residence time (Table 1). As meteorological measurements were not made during this study, we utilized two regional-scale sources of evaporation to support this calculation. The residence times varied between 1.8 and 10.4 years. Using the NARR evaporation (583 mm/yr) compared to the Alberta Government evaporation (660 mm/yr) resulted in a slightly greater residence time (12%). These relatively short residence times and the closed basin lake systems suggest that the lakes in question are well mixed and have climatically driven hydrologic budgets (van der Kamp, Keir, and Evans 2008).

Conceptualization of small prairie lake hydrologic budgets

The opposing views of prairie lake hydrologic budgets that either rely largely on groundwater input (e.g. Crow and Schwartz 1985; Schwartz and Gallup

Table 1. Lake attributes from the atlas of Alberta lakes and the North Saskatchewan Watershed Alliance, mean stable isotope composition from 2016-2017 sampling, and results of IMB calculations. The equations, terms, and data sources for IMB calculations are provided in S1-5.

Lake	Elevation (masl)	Lake Area (km ²)	Mean Lake Depth (m)	Lake Volume (m ³)	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)	d-excess (‰)	E/I	Residence Time (yrs) using NARR Evaporation (583 mm)	Residence Time (yrs) using AESRD Evaporation (660 mm)
Mayatan	735	1.4	5.7	7695000	-6.50	-86.65	-34.63	0.618	5.82	5.14
Hubbles	733	0.4	10.1	4040000	-6.60	-87.81	-35.04	0.597	10.35	9.14
*Cottage	738	0.4	-	~760000	-5.70	-84.85	-39.28	0.814	2.91	2.57
Spring	740	0.8	1.9	1520000	-6.54	-87.24	-34.93	0.610	1.99	1.76
Jackfish	731	2.4	3.4	6904000	-6.58	-87.25	-34.62	0.602	2.97	2.62
Hasse	729	0.9	3.5	3150000	-6.48	-85.41	-33.53	0.621	3.73	3.30

*The depth of Cottage lake is unknown and assumed to be similar to Spring lake located 1.5 km away, leading to an assumed lake volume for the residence time estimate.

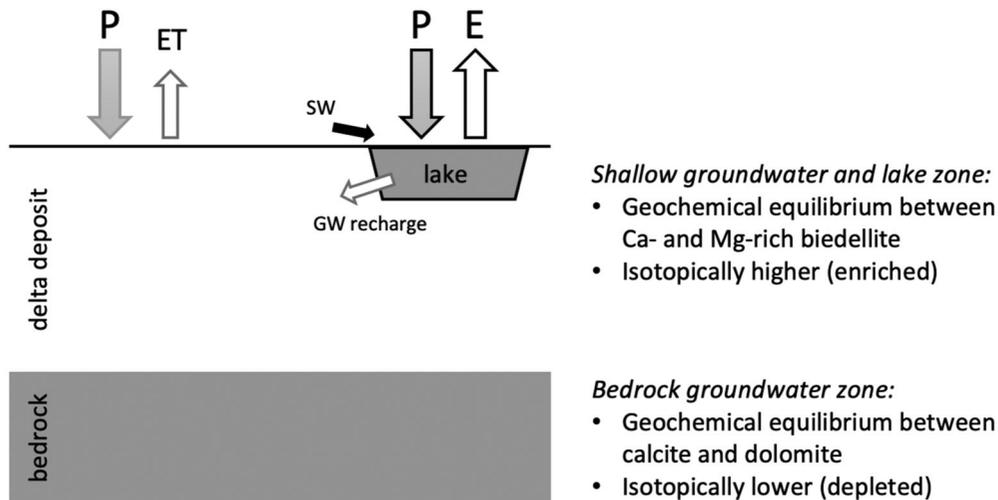


Figure 10. Conceptualization of stratified hydrologic budget for Parkland County lakes and surrounding groundwater. P = precipitation, E = evaporation, ET = Evapotranspiration, SW = surface water inflows from local runoff; GW recharge = lake water lost to groundwater.

1978) or minimal groundwater input but major input by surface runoff (e.g. LaBaugh et al. 1997; van der Kamp, Keir, and Evans 2008, Xiao et al. 2018) can be considered end-members of a spectrum. Many small lakes on the prairie landscape could be small, visible outcrops of the shallow groundwater system within the thick/heterogeneous sediments overlying bedrock (Webster et al. 2006). Yet, the presence of a subsurface hydraulic connection that can propagate changes in pressure (e.g. lake levels and groundwater levels) does not imply physical movement of water. Appreciable water movement requires a hydraulic gradient and sufficient permeability. Where small lakes are well-connected to permeable reservoirs, such as extensive sand/gravel deposits, water may exchange more freely between lakes and groundwater, and have a significant role in controlling the hydrologic budget of a lake (Rosenberry et al. 2015). Where the connection may not support an appreciable water exchange, the role of groundwater is not as great. Combined

with lack of observed outflows on these lakes, the IMB calculations suggest 40% of water inflows could be lost to groundwater recharge. The geochemical and isotopic evidence for the Parkland County lakes in this study indicates that there is little connection between the lakes and the deeper bedrock groundwater, but some connection between the lakes and shallow groundwater. The findings of this study suggest a stratified conceptual model (Figure 10), whereby vertical interaction with the climate and localized surface runoff to the lakes drives the lake and shallow groundwater hydrological budgets, and that the bedrock groundwater is part of a more regional system. The combination of activity plots and isotope mass balance demonstrates that water provenance and a general lake budget can be learned through a community-supported research project. Further investigation of the shallow groundwater is needed to determine the depth of water-cycling related to evaporative enrichment, but this appears to be at least 6 m. Additional investigation of the shallow

groundwater regime could be expanded to include a greater number of small lakes in this region, establish the water table configuration, and analyse hydraulic head gradients around small terminal lakes in the Alberta prairies.

Conclusions

Since the 1970s, most lakes in Parkland County have experienced declining water levels. This study suggests that there is minimal groundwater exchange to and from the lakes, and that these lakes are terminal lakes with some runoff input and little to no stream output. In sum, the lake water levels are dominantly controlled by an evaporation - precipitation balance, making for short residence times in many of the lakes in the area. There may also be water loss from the lakes to the shallow groundwater system in the delta sediments above the bedrock. During the time of study, declining water levels were likely a product of a drier summer period with less frequent and smaller precipitation events, while maintaining normal summer temperatures. Should this trend continue, it could indicate a shift in the evaporation - precipitation balance towards a drier climate, which would be supported by the lack in seasonal variation and consistently enriched lake water isotopes in both the lakes and shallow groundwater. This is in contradiction to much of the current climatic modelling which suggests that the Canadian prairies will become warmer and wetter over the course of climate change (Zhang et al. 2016). However, further work is needed to determine how changes in the local climate would impact these lakes before any conclusions can be drawn about the climatically driven changes of lake water levels in the area.

Statement of data availability

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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