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Stable isotope mass balance of fifty lakes in central Alberta: Assessing the role of water balance parameters in determining trophic status and lake level

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ABSTRACT

Study region: This study spans the Prairie/parkland/boreal transition in central Alberta, including lakes in the Athabasca, North Saskatchewan, Battle River and Red Deer Basins.

Study focus: Stable isotopes of water, oxygen-18 and deuterium, were measured in a network of 50 lakes during 2008 and 2009. The lakes are the subject of recent concern due to widespread lake level decline and development of eutrophic conditions that have been attributed to climate and land-use impacts. An isotope mass balance method was applied to estimate evaporation/inflow, water yield, and water residence times to assess relationships between water balance and lake status.

New hydrological insights: Water yield was found to range from near 0 to 235 mm, evaporation/inflow was found to range from 18 to 136 %, and water residence time ranged from 2.3 to 58 years. The healthiest lakes in terms of trophic status are deep lakes with smaller catchments with long residence times. These lakes may have stable or variable water levels. Distressed lakes are often shallow prairie lakes with limited inflow and shorter residence times, and situated in areas with higher evaporation rates. High conductivity and high sulfate in some eutrophic lakes, attributed to saline groundwater inflow, may inhibit algae and cyanobacterial growth, thereby promoting healthier conditions. Extended drought under climate warming is expected to cause eventual decline of water levels in a greater number of lakes.

1. Introduction

Lakewatch is the flagship program of the Alberta Lake Management Society, a volunteer organization with the objective of collecting and interpreting water quality data on Alberta Lakes, educating lake users about their aquatic environment, encouraging public involvement in lake management and facilitating cooperation and partnerships among government, industry, the scientific community and lake users. Approximately 93 lakes in central Alberta have been studied under the program. Recent concerns that have sparked interest in the lakes include water-level decline and high concentrations of nutrients, thought to be linked to land-use and climatic changes (Alberta Environment, 2013).

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The Prairie Provinces have experienced warming of about 1.6 °C during the past century with the greatest upward trend occurring since the 1970s (Sauchyn and Kulshreshtha, 2008). The region is also particularly drought-prone mainly due to its location in the lee of the Western Cordillera and distance from large moisture sources (Bonsal et al., 2013). Multi-decadal climate variability is expected to continue to produce cycles of drought with the severity of drought possibly worsening due to anticipated warming in the 21st century (Bonsal et al., 2013). Understanding the hydrological response of lakes to climatic fluctuations is of primary importance for long-term planning and water management on the Prairies (van der Kamp et al., 2008).

The lakes monitored by Alberta Lake Management Society are important particularly for recreational use (e.g. cottaging, camping, boating, swimming, fishing), for drinking water supply, and as wildlife habitat. The lakes are under increasing stress from both climate and land use changes including agriculture, forestry, and rural development. While lake levels have been monitored in many of the lakes during the past few decades, relatively limited information is available on important water balance parameters such as runoff to the lakes, outflow from the lakes, and evaporation. Residence times, while available for some of the lakes, have been estimated based on incomplete inflow records. Several of the lakes are entirely ungauged. In order to gain a better understanding of the causes of water-level decline in the lakes, and the reasons behind water quality degradation, water sampling was extended to include stable isotopes of water beginning in 2008. The overall objective of the program was to provide quantitative estimates of evaporation/inflow, water yield and water residence time for the lakes for the purpose of conducting an assessment of the role of key water balance components in driving changes in water level and trophic status at specific sites and across the region. Drought, which is widely observed in Prairie lakes for several decades, is thought to be a primary driver of these changes (van der Kamp et al., 2008).

Previous studies in Alberta have applied the stable isotopes of water as a method for establishing hydrologic control for lakes in sustainable forest management studies (Prepas et al., 2001; Gibson et al., 2002), critical loads assessment (Bennett et al., 2008; Gibson et al., 2010a,b), flood history studies (Yi et al., 2008; Brock et al., 2009; Wolfe et al., 2012), and regional runoff assessment (Gibson et al., 2015a). The method has been tested for both shallow and stratified lakes (Gibson et al., 2002). Previous isotope balance studies of closed-basin lakes in Saskatchewan include Pham et al. (2012) who found that long-term mean chemical characteristics were regulated mainly by changes in winter precipitation or groundwater influx. van der Kamp et al. (2008) also described regional patterns in water level decline in closed-basin lakes across south-central and east-central Alberta though central and southeast Saskatchewan. Our study differs in scope as it is less targeted to climate-sentinel lakes (see Pham et al., 2012). We look at a range of lakes, including closed-basin lakes as well as lakes with abundant throughflow, and Prairie and boreal/parkland lakes, in an effort to identify broader patterns of water balance among a representative range of lakes across central Alberta. To our knowledge, this is the first integrated regional analysis of water balance of lakes for this area.

1.1. Study area

Fifty lakes were sampled in four major river basins including the Athabasca, Beaver River, Battle, and Red Deer river basins (Fig. 1). The study area spans Prairie to boreal ecoregions ranging over Aspen parkland, Boreal Transition and Mid-Boreal Upland subregions (Canada, 1995). The area consists of landforms of glacial, fluvio-glacial, and lacustrine origin forming rolling morainal uplands and flat lowlands. Glacial till typically ranges from 15 to greater than 150 m thick (Pawlowicz and Fenton, 1995). Vegetation ranges from grassland to aspen and boreal forest, with abundant wetlands, permanent streams and lakes. Agriculture, oil and gas extraction, and municipal water supply are the dominant water users. While the Athabasca and North Saskatchewan Rivers are conduits for alpine runoff originating from the Rocky Mountains, the Battle River, Beaver River and Red Deer Basins are derived entirely from local runoff, making water supply more limited. Lakes in the region can be divided into three general types: Prairie lakes characterized by shallow depth with a gently sloping bottom, deeper lakes with steep sides, and lakes formed by impoundments of surface water in abandoned glacial meltwater channels. Deeper lakes are typically dimictic and so are stratified in summer, whereas shallow lakes are commonly well-mixed, monomictic or polymictic.

The climate is continental, with average annual precipitation ranging from 380 mm in the southeast (Clear Lake) to greater than 500 mm in the northeast (Goose L.). Annual temperature is close to 1.5 °C with mean monthly temperatures ranging from approximately −15 °C (January) to +15 °C (July). Lake evaporation ranges from about 430 to 576 mm (Mesinger et al., 2006). Climate conditions during 2008 and 2009 were similar to long-term (1948–2013) averages, with precipitation falling within 5% of normal and temperature within 0.4 °C of normal for the Prairie and Northwestern Forest regions (Environment Canada, 2013).

2. Methods

Water samples were collected in August or September during water quality monitoring surveys by Lakewatch volunteers and by a University of Victoria student. Samples for isotopic analysis were collected as depth-integrated samples where possible from the center of the lake. Due to more limited resources in 2009, the samples were collected from nearshore areas at mid-depth, commonly from docks or boat launches. Samples were collected in HDPE bottles that were tightly sealed to avoid evaporation.

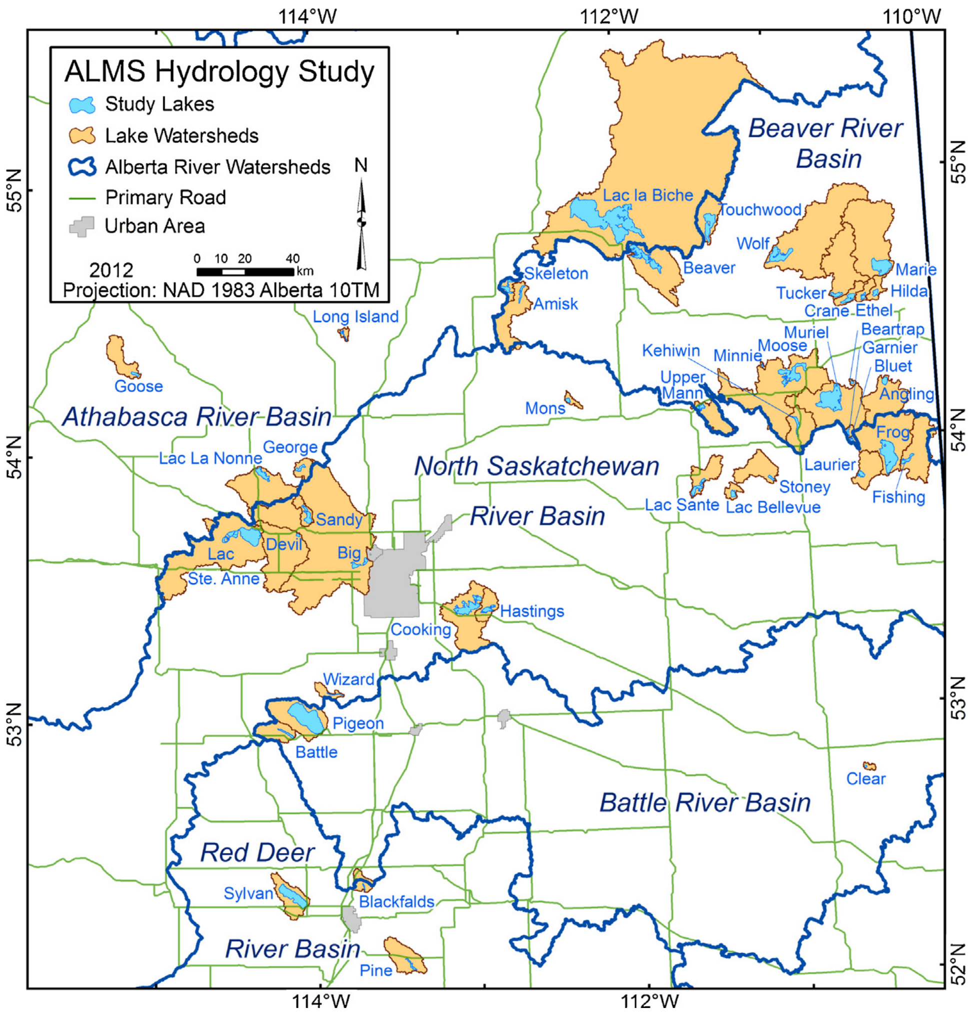

Fig. 1. Map showing location of lakes sampled by Alberta Lake Management Society in 2008 within the Beaver River watershed and surrounding basins. Watershed areas are also shown.

Water balance is characterized using an isotope mass balance model (IMB) demonstrated previously for lakes in northern Canada (Gibson et al., 2002, 2010a,b, 2015a; Bennett et al., 2008). The IMB, which assumes well-mixed conditions and steady-state hydrology, is used to estimate evaporation/inflow based on the isotopic offset between the evaporatively enriched lake water and precipitation input. With this approach, potential stratification is not characterized but rather the average isotopic composition of the whole water body is considered. Precipitation and evaporation estimates for the site are then used to constrain ungauged inflows and outflows to the lake. The method is described in a recent review by Gibson et al. (2015b). A brief overview of the key concepts is presented below.

The annual water balance and isotope balance for a well-mixed lake in isotopic and hydrologic steady state can be written, respectively as:

$$I = Q + E \quad (\mathrm{m}^3 \times \mathrm{year}^{-1}) \tag{1}$$

$$I\delta_I = Q\delta_Q + E\delta_E \quad (‰ \times \mathrm{m}^3 \times \mathrm{year}^{-1}) \tag{2}$$

where I, Q and E are lake inflow, outflow and evaporation rates ($\mathrm{m}^3 \times \mathrm{year}^{-1}$), and δ_I, δ_Q and δ_E are the isotopic compositions of inflow, outflow and evaporation fluxes (‰), respectively. The evaporation/inflow (E/I) can be estimated by rearranging Eq. (2), and substituting $Q = I - E$ from Eq. (1):

$$\frac{E}{I} = \frac{(\delta_I - \delta_Q)}{(\delta_E - \delta_Q)} \quad (\text{dimensionless}) \tag{3}$$

For well-mixed lakes, we can assume $\delta_Q \approx \delta_L$ where δ_L is the isotopic composition of lakewater. For headwater lakes, the isotope composition of inflow is often close to that of precipitation, i.e. $\delta_I \approx \delta_P$. However, isotopic composition of inflow may in some cases need to account for inputs from upstream lakes and or groundwater (see Gibson and Reid, 2014). Isotopic composition of evaporate δ_E can be estimated using the Craig and Gordon (1965) linear resistance model:

$$\delta_E = \frac{\left(\left(\delta_L - \varepsilon^+\right)/\alpha^+ - h\delta_A - \varepsilon_K\right)}{\left(1 - h + 10^{-3} \times \varepsilon_K\right)} \quad (‰) \tag{4}$$

where h is the relative humidity (decimal fraction), $\delta_{\rm A}$ is the isotopic composition of atmospheric moisture (‰), ε^+ is the equilibrium isotopic separation (‰), α^+ is the equilibrium isotopic fractionation whereby $\varepsilon^+ = \alpha^+ - 1$, and $\varepsilon_{\rm K}$ is the kinetic isotopic separation (‰). Estimation of the isotopic separations was described in Gibson et al. (2015b). Substitution of Eqs. (4) into (3) yields:

$$\frac{E}{I} = \frac{(\delta_L - \delta_I)}{(m(\delta^* - \delta_L))} \quad \text{(dimensionless)} \tag{5}$$

where,

$$m = \frac{\left(h - 10^{-3} \times \left(\varepsilon_{\rm K} + \varepsilon^+/\alpha^+\right)\right)}{\left(1 - h + 10^{-3} \times \varepsilon_{\rm K}\right)} \quad \text{(dimensionless)} \tag{6}$$

and

$$\delta * = \frac{\left(h\delta_{\rm A} + \varepsilon_{\rm K} + \varepsilon^+/\alpha^+\right)}{\left(h - 10^{-3} \times \left(\varepsilon_{\rm K} + \varepsilon^+/\alpha^+\right)\right)} \quad ‰ \tag{7}$$

As the inflow to a lake is comprised of precipitation on the lake surface as well as ungauged inflow R, i.e. $I = P + R$, we can estimate R for headwater lakes by substitution of Eq. (5):

$$R = \frac{E}{x - P} \quad (\text{m}^3 \times \text{year}^{-1}) \tag{8}$$

where $x = E/I$, and $E = e \times \text{LA}$ and $P = p \times \text{LA}$; e and p are the annual depth-equivalent of evaporation and precipitation (m $\times$ year^{-1}), and LA is the lake area (m^2). Water yield, or the depth-equivalent runoff, can then be estimated as

$$Wy = \frac{R}{\text{WA} \times 1000} \quad (\text{mm} \times \text{year}^{-1}) \tag{9}$$

where WA is the watershed area.

Note that isotopic composition of atmospheric moisture is commonly estimated based on the assumption of isotopic equilibrium with precipitation (Gibson et al., 2015b) as described later on.

In cases where bathymetric surveys of the lakes have been conducted so that volume (V) is known, the isotope-based water residence time (τ) is estimated using

$$\tau = \frac{xV}{E} \quad (\text{year}) \tag{10}$$

which accounts for both water yield and precipitation input to the lakes.

2.1. Watershed parameters

Application of the IMB model required delineation of watershed areas, lake areas, and lake elevations for each of the study lakes. This was accomplished using ArcGIS applying the ArcHydro tools. Each watershed was delineated upstream of its lake outlet, which was identified based on hydrographic and elevation data. In some cases, two or more partial watersheds had to be merged together to create the final watershed polygon. The planimetric area of both the lake and watershed polygons was calculated in the ArcGIS program based on the equal area projection. Watershed parameters are provided in Table 1.

2.2. Climate parameters

Climate parameters were obtained from the North American Regional Reanalysis (NARR) dataset (Mesinger et al., 2006). Climatological average monthly fields (based on data from 1979–2003) were extracted for the grid cells corresponding to the location of each of the study lakes. Parameters extracted included: surface total precipitation (kg m^{-2}), 2-m relative humidity (%), surface evaporation (kg m^{-2}), and 2-m temperature (K). The evaporation flux-weighting approach (see Gibson et al., 2015b) was used to weight estimates of relative humidity and temperature so that the water balance calculations were more representative of the evaporation season when the isotopic enrichment of lake water occurs. Temperature used in the calculations ranged from 10.5 to 13.3 °C for individual lakes, with weak gradients observed across the region. In contrast, relative humidity, which ranged from 59 to 66 %, was found to increase systematically with latitude, and is greater in the forested northern areas than in the southern Prairies.

Table 1
Characteristics of lakes including isotope-based estimates of evaporation/inflow (E/I), water yield (W_Y), and residence time.

	Lake	Δ Lake level	Latitude (°)	Longitude (°)	Elevation (masl)	Watershed area (km^2)	Lake area (km^2)	Volume ($\times 10^6$ m^3)	Maximum (m)	Mean (m)	Lake evaporation (mm)	Precip. (mm)	$\delta^{18}O$ (‰)	δ^2H (‰)	E/I (‰)	W_Y (mm)	Residence time (year)
1	Pine S.L.	~	52.1	−113.5	889	154.9	4	20.6	12.2	5.3	454	449	-10.79	−106.8	31.8	26	3.6
2	Sylvan Lake	~	52.35	−114.2	936	148.4	42.2	412	18.3	9.6	508	487	−8.95	−92	47.2	235	9.1
3	Blackfalds L.	n.d.	52.39	−113.7	840	53.7	1.1	n.d.	n.d.	n.d.	493	472	−8.27	−91.5	53.1	10	
4	Clear Lake	n.d.	52.76	−110.6	966	11.6	0.9	n.d.	n.d.	n.d.	410	387	−8.23	−89.3	61.8	24	
5	Battle Lake	~	52.96	−114.2	837	110.6	4.5	31.6	13.1	6.9	545	512	−13.68	−120.7	18	106	2.3
6	Pigeon Lake	~	53.01	−114	849	275.5	97.3	603	9.1	6.2	518	500	−8.78	−90.5	55.7	235	6.7
7	Wizard L. W.	~	53.11	−113.9	784	40.3	2.6	14.8	11	6.2	518	500	−9.26	−97.5	48.6	39	5.4
8	Wizard L. E.	~	53.11	−113.9	784	40.3	2.6	14.8	11	6.2	518	500	−9.34	−98.1	48	40	5.3
9	Cooking Lake	↓	53.42	−113	734	330.8	36.4	60.9	4.6	1.7	464	458	−4.62	−70.4	134	−14	4.8
10	Hastings Lake	↓	53.42	−112.9	736	411.2	8.5	20.9	7.3	2.4	464	458	−7.9	−89.4	68.6	5	3.6
11	Sandy Lake S.	↓	53.47	−114	698	55.1	9.6	25.96	4.4	2.6	533	497	−5.06	−74.7	118	−9	6
12	Big Lake	n.d.	53.6	−113.7	n.d.	2691	8.3	n.d.	0.8	n.d.	473	481	−9.62	−99.4	48	2	
13	Lac St. Anne E.	~	53.71	−114.4	719	714.4	56.6	263	9	4.8	534	500	−7.54	−86.3	73.2	20	6.4
14	Devil's Lake	~	53.71	−114.1	679	1091	1.6	9.18	10	4.4	502	488	−12.17	−114.7	28.5	2	3.3
15	Lac St. Anne W.	~	53.71	−114.5	719	714.4	56.6	263	9	4.8	564	515	−7.95	−89.9	67	28	5.5
16	Sandy Lake N.	↓	53.77	−114	698	25.1	2.4	3.43	4.4	2.6	502	488	−4.72	−75.4	136	−12	3.9
17	Lac Bellevue	↓	53.81	−111.3	645	31.9	4.6	n.d.	n.d.	n.d.	449	418	−7.51	−84.6	74.7	31	
18	Lac Santé	↓	53.83	−111.6	604	113.6	10.9	n.d.	25	n.d.	462	426	−6.7	−79.8	85.9	12	
19	Laurier Lake	↑	53.85	−110.5	566	126.3	5.1	n.d.	6.6	n.d.	453	406	−6.67	−82.5	86.8	5	
20	Stoney Lake	n.d.	53.86	−111.1	580	141.2	2.3	n.d.	n.d.	n.d.	461	415	−7.55	−89.2	74.1	3	
21	Frog Lake	↓	53.89	−110.3	574	640.1	58.3	n.d.	28	n.d.	453	406	−6.82	−78.6	85.1	13	
22	Fishing Lake	n.d.	53.91	−110.2	570	246.3	6.9	n.d.	9.5	n.d.	453	406	−7.38	−83.9	75.9	5	
23	Lac La Nonne	↓	53.94	−114.3	663	295.9	12.9	92.3	19.8	7.8	525	496	−7.96	−90.3	68.4	12	9.3
24	George Lake	~	53.96	−114.1	682	51.3	4.9	n.d.	n.d.	n.d.	507	486	−5.06	−75.4	128	−10	
25	Bluet Lake	n.d.	53.99	−110.6	626	11.2	1.3	n.d.	9.5	6.5	459	413	−6.72	−81.9	89.3	13	
26	Garnier Lake N.	↓	54.03	−110.6	706	25.6	2	n.d.	9.5	6.5	459	413	−6.49	−82.7	94.4	6	
27	Kehewin Lake	~	54.06	−110.9	540	168.4	6.6	n.d.	11.6	6.7	461	415	−8.2	−91.4	65.6	12	
28	Muriel Lake	↓	54.06	−110.7	560	455.7	68.9	424	10.7	6.6	459	413	−7.62	−79	73.9	37	9.9
29	Upper Mann L.	n.d.	54.14	−111.5	616	122.5	5.7	26.1	9.1	5.7	438	429	−5.45	−76.7	117	−3	12.2
30	Mons Lake	~	54.19	−112.4	606	19.6	2.7	n.d.	7	n.d.	431	441	−7.19	−86.7	82.4	13	
31	Bear Trap Lake	~	54.2	−110.5	573	5.5	1.5	n.d.	n.d.	n.d.	460	414	−7.33	−85.6	80.1	58	
32	Angling Lake	~	54.2	−110.3	557	229.4	5.9	n.d.	n.d.	n.d.	463	410	−9.61	−97.8	50.5	13	
33	Moose Lake	↑	54.25	−110.9	534	865.6	40.5	230	19.8	5.6	455	418	−7.62	−86.3	74.8	9	9.3
34	Minnie Lake	↓	54.29	−111.1	554	4	0.9	6.9	23.8	8.2	455	418	−6.04	−80.6	105	4	18.2
35	Goose Lake	~	54.32	−115.1	721	116.1	3.2	n.d.	6	4.5	576	513	−12.17	−114.4	29.2	41	
36	Long Island L. S	↑	54.44	−113.8	696	15.8	2.2	n.d.	n.d.	n.d.	504	475	−6.86	−87.1	93.3	11	
37	Long Island L. N	↑	54.46	−113.8	696	15.8	2.2	n.d.	n.d.	n.d.	504	475	−6.87	−86.2	93.2	11	
38	Crane Lake	↓	54.51	−110.5	546	53.2	10.3	77.4	26	8.3	493	424	−7.71	−88.4	74.8	56	11.4
39	Hilda Lake	↑	54.53	−110.4	546	90.3	3.5	22.6	14	6.2	493	424	−6.93	−83.2	87.8	6	11.3
40	Tucker Lake	n.d.	54.53	−110.6	554	309.9	6.7	19	7.5	2.9	479	424	−10.05	−101.5	47.7	13	2.8
41	Ethel Lake	n.d.	54.53	−110.4	536	633.9	4.9	32.2	30	6.6	493	424	−9.47	−95.8	52.7	4	7
42	Marie Lake	~	54.6	−110.3	550	500.5	37.4	484	26	14	493	424	−9.78	−97.2	50	45	13.1
43	Skeleton L. S.	↓	54.61	−112.7	624	42.6	7	51.4	17	6.5	443	452	−7.09	−84.5	88.6	10	14.6
44	Amisk L.S.	~	54.61	−112.6	612	166	2.9	54.6	60	19.4	443	452	−9.93	−101.2	49.8	8	21.2
45	Amisk Lake	~	54.61	−112.6	612	251.4	2.3	25.1	34	10.8	443	452	−9.91	−102.4	49.9	4	12.5
46	Skeleton L. N.	↓	54.64	−112.7	624	8.5	1.7	51.4	17	6.5	443	452	−7.22	−86.9	86.7	15	57.5
47	Wolf Lake	~	54.7	−111	597	717.4	31.4	289	38.3	9.2	458	426	−9.99	−98.2	50	22	10.1
48	Beaver Lake	↓	54.72	−111.8	559	320.7	38.9	234	15.2	7.1	431	435	−6.96	−83.5	87.5	8	12.2
49	Touchwood L.	↑	54.83	−111.4	631	140.3	28.9	430	40	14.8	438	428	−9.31	−94.2	58.7	82	20
50	Lac La Biche	~	54.86	−112.1	532	4371	236.5	1960	21.3	8.4	456	440	−10.5	−101.7	44.7	33	8.1

Note: ~ - relatively stable; ↑ - increasing; ↓ - declining.

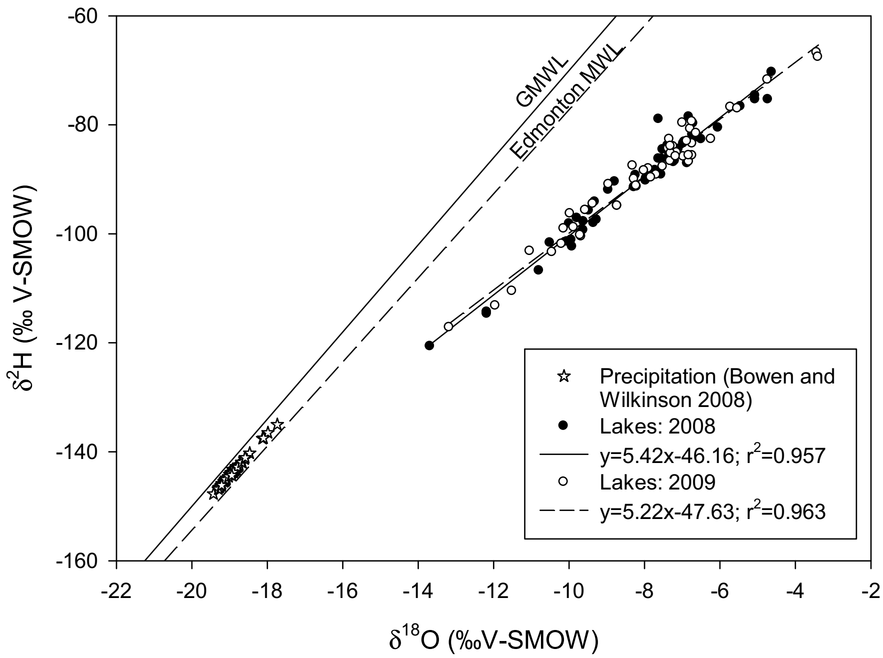

Fig. 2. δ^2H–δ^{18}O plot illustrating evaporative isotopic enrichment in lakes relative to precipitation interpolated for the sites based on the algorithm of Bowen and Wilkinson (2002) but tuned to CNIP data in the region. Also shown are the Global Meteoric Water Line of Craig (1961) given by $\delta^2H = 8\delta^{18}O + 10$ and the meteoric water line for Edmonton given by $\delta^2H = 7.67\ \delta^{18}O - 0.14$ (Peng et al., 2004). Note that regressions for 2008 and 2009 lakes suggest very similar regional evaporation lines.

2.3. Isotopic parameters

Monthly precipitation δ^{18}O and δ^2H estimates were obtained for each lake location based on empirically-derived relationships between latitude and elevation (Bowen and Wilkinson, 2002), but tuned to regional isotopic data from the Canadian Network for Isotopes in Precipitation (CNIP; Birks et al., 2003). Annual averages of precipitation isotope fields were amount-weighted using monthly precipitation amount estimates obtained from the NARR climatology dataset. Annual isotopic composition of atmospheric moisture was estimated based on the same monthly precipitation records but using NARR evaporation-flux-weighting and assuming isotopic equilibrium between precipitation and atmospheric moisture.

2.4. Geochemical parameters and statistical analysis

Geochemical parameters were measured on water samples collected using standard protocols of Alberta Environment for lake sampling (Alberta Environment, 2006). Analytical methods are described by Hatfield Consultants (2011). Potential relationships between lake types and geochemical/landscape characteristics were evaluated using principle component analysis (PCA), a multivariate statistical technique that transforms and extracts meaningful information from large datasets with multiple variables. Using PCA, we found linear combinations of original variables to represent a large part of variance in the dataset. The resulting principal components were then used to represent the dataset without losing significant information, but reducing complexity. In this study, we use biplots, which are overlays of the scores of individual lakes, with loading of variables such as total dissolved solids (TDS), major ions geochemistry, water yield (WY) and wetland proportion (wetland%), to provide a statistical overview. Proximity in the biplot is an indicator of similarity between lakes as well as an indicator of the importance of driving variables. PCA was carried out using SIMCA-P+ (V12.0, Umetrics AB Umeå, Sweden).

3. Results

3.1. Isotope characteristics

Annual precipitation estimates span a range in δ^{18}O from −19.43 to −17.73 ‰ and in δ^2H from −147.8 to −135.0 ‰. On a δ^2H–δ^{18}O plot, the results fall intermediate between the Global Meteoric Water Line (GMWL) of Craig (1961) given by $\delta^2H = 8\delta^{18}O + 10$ and the Local Meteoric Water Line (LMWL) for Edmonton given by $\delta^2H = 7.72\delta^{18}O + 0.031$. Precipitation falls approximately at the intersection between the local evaporation line and the meteoric water lines.

Lake waters for 2008 were found to plot along a local evaporation line defined by $\delta^2H = 5.42\delta^{18}O - 46.16$ ($r^2 = 0.957$) (Fig. 2). Lake waters for 2009 were found to plot along a very similar local evaporation line defined by $\delta^2H = 5.22\delta^{18}O - 47.63$

($r^2 = 0.963$). A regression of 2008 versus 2009 lake waters revealed nearly a 1:1 correlation ($\delta^{18}O_{2009} = 0.99\delta^{18}O_{2008} + 0.19$; $r^2 = 0.901$). A comparable evaporation line is estimated from regression of a recent lakewater dataset compiled for the adjacent Athabasca Oil Sands region between 56 and 59°N, but with a slightly lower δ^2H intercept ($\delta^2H = 5.20\delta^{18}O - 50.6$; see Gibson et al., 2015a). Similar evaporation lines have also been reported for lake surveys in nearby Manitoba and Saskatchewan (Gibson et al., 2010b).

Degree of offset along the LEL is found to be generally indicative of the fraction of water loss by evaporation. Accordingly, lakes that plot on the LEL closer to meteoric water input are generally more flushed than lakes that are more isotopically enriched. Lakes plotting at the depleted end of the spectrum tend to have permanent or intermittent outflow streams. The most enriched lakes are found to be closed-basin lakes where evaporation balances or exceeds inflow. Outflow streams may be completely absent in these cases. Similarity of the isotopic results in 2008 and 2009 despite slightly different sampling strategies suggests that the water samples were fairly representative for each lake. Quantification of the water balance based on isotopes is presented in section.

3.2. Geochemical characteristics

A summary of average lake geochemistry based on data collected during 1980–2008, as provided by Lakewatch, is presented including classification of trophic status (Table 2). In general, lakes are alkaline (pH 8–9), have moderate to high total dissolved solids (TDS: 130–1300 mg), and are well buffered from acidic deposition due to abundance of carbonate minerals in till and bedrock aquifers. Total dissolved solids are thought to depend largely on degree of connection to groundwater sources which may be saline in some areas. Dissolved organic carbon ranges from 0 to 100 mg, and tends to be highest in drought-affected lakes.

Lakes span a range of trophic states from mesotrophic to hyper-eutrophic, and usually contain between 1000 and 4000 μg total nitrogen, 15–250 μg of total phosphorous, and chlorophyll-a concentrations up to 103 μg. Classification of trophic status used here is based on the method of Nurnberg (1996). Secchi depths typically ranged from 0.5 to 5 m and vary seasonally as influenced by silt suspension during snowmelt and algal biomass production which tends to increase as summer progresses.

A principal component analysis (PCA) biplot is shown for lakes, including loadings of the individual geochemical variables, with lakes differentiated by trophic status (Fig. 3).

The plot confirms that hyper-eutrophic lakes are driven mainly by increased nutrient levels, whereas eutrophic lakes appear in many cases to be distinguished by higher alkalinity, hardness, HCO_3, CO_3, and Mg, as well as electrical conductivity and TDS (Fig. 3). The latter effect is interpreted as being from the influence of saline groundwater.

High conductivity and high sulfate in these lakes tends to inhibit growth of algae and cyanobacteria despite eutrophic nutrient levels (Lakewatch 2012). However, differences in geochemical properties between lakes may be more subtle, as shown by the abundance of mesotrophic, eutrophic and hypertrophic lakes that plot close to the origin.

3.3. Lake levels

Water levels records are available for 42 of the 50 lakes, with records dating back to the 1930s in some cases, although records are often discontinuous. Our analysis focuses on the current status of water levels, classifying them as relatively stable, increasing or decreasing during the past decade (see Table 1). Many factors influence water balance and water levels across the region including size of drainage basin, precipitation, evaporation, water consumption, groundwater influences and the efficiency of the outlet channel structure at removing water from the lake (Lakewatch 2014). A thorough analysis of temporal variations in lake levels in relation to climatic trends, while warranted, is beyond the the scope of this contribution.

3.4. Water balance calculations based on stable isotopes

Water balance results including evaporation/inflow (E/I) and water yield (W_Y) are presented in Table 1 for 50 lakes in Athabasca, Beaver River, Battle River and Red Deer basins. Residence time estimates are also provided for 31 lakes where volume estimates were available (see Table 1). Calculations are based on Eqs. (5), (9) and (10), respectively utilizing the 2008 dataset, acknowledging that similar results would be obtained using the 2009 dataset. The derived parameters are approximately integrated over the residence time of water in the lakes, thus, providing a contemporary perspective of water balance. Note that assessments for individual basins of Wizard Lake North-South, Lac St. Anne East-West and Long Island Lake North-South utilized the watershed areas and volumetric data for the entire lake, so are very similar. It is important to note that some calculation assumptions such as hydrologic steady state (i.e. constant water level) may not be strictly correct for lakes where water levels are observed to be changing (see Table 1). However, the calculations provide a first-approximation of water balance conditions that enable very relevant comparisons to be made between lakes, and as we will show, provide a basis for looking at the physical drivers of water balance and their influence on geochemistry.

Overall, lake evaporation exceeds precipitation by close to 6% on average in this region (~30 mm·year^{-1}), accounting for roughly 72% of total water losses, the remainder being surface and/or groundwater outflow. Water yield (runoff) to lakes is slightly less than the precipitation-evaporation deficit, averaging 27 mm·year^{-1} (depth integrated over land area in watershed), although this ranges upwards of 235 mm·year^{-1} for some well-connected lakes (i.e. Sylvan Lake, Pigeon Lake).

Table 2
Geochemical parameters based on available monitoring data, 1980–2008.

Lake #	Trophic status	pH	Cond (μS/cm)	Na (mg·L^{-1})	Ca (mg·L^{-1})	K (mg·L^{-1})	Mg (mg·L^{-1})	Cl (mg·L^{-1})	SO_4 (mg·L^{-1})	HCO_3 (mg·L^{-1})	CO_3 (mg·L^{-1})	DOC (mg·L^{-1})	TP (μg·L^{-1})	TDP (μg·L^{-1})	TKN (μg·L^{-1})	Total N (mg·L^{-1})	NO*x*–N (μg·L^{-1})	NH_4–N (μg·L^{-1})	Chl–a (μg·L^{-1})	Secchi depth (m)	TDS (mg·L^{-1})	Hardness ($CaCO_3$) (mg·L^{-1})	Total alkalinity (mg·L^{-1})
1	E	8.7	726	122	22	10	24	10	83	371	23	18	65	27	1617	2	8	99	25	2.1	450	160	333
2	M	8.8	594	66	15	8	37	2	14	353	23	8	57	7	712	1	3	9	5	4.7	347	194	327
3	H	8.6	775	86	28	29	28	32	79	347	14	37	219	148	3520	3	83	42	61	1.3	467	184	309
4	M	8.7	479	21	18	6	43	2	11	292	18	9	24	9	846	1	5	29	5	3.2	261	219	268
5	E	8.5	343	22	36	4	11	3	9	197	6	9	33	12	669	1	4	14	15	3.1	190	134	171
6	E	8.4	283	16	26	5	10	1	5	179	4	7	33	16	761	1	1	3	14	2.1	155	107	152
7	E	8	302	30	31	7	8	5	4	209	3	0	46	12	1058	1	9	22	20	2	197	127	175
8	E	8	302	30	31	7	8	5	4	209	3	0	46	12	1058	1	9	22	20	2	197	127	175
9	H	8.9	1402	239	30	44	49	17	284	419	42	100	251	63	6510	10	8	40	83	0.6	1019	277	414
10	H	8.9	917	98	29	29	46	10	221	238	26	36	136	51	3730	8	12	515	74	0.9	573	258	238
11	H	9	801	151	9	17	10	8	6	200	286	32	146	30	4669	4	9	192	72	0.9	482	78	410
12	H	9	618	70	31	8	21	41	109	154	16	19	134	48	1576	2	17	55	13	0.6	372	215	152
13	H	8.4	305	16	30	7	9	2	10	176	6	9	48	18	919	1	3	24	18	2.2	165	112	152
14	H	8.5	633	75	38	7	19	12	71	285	13	18	115	48	1475	1	10	100	45	2.3	411	164	249
15	H	8.5	288	16	27	7	8	2	8	162	5	11	44	12	1181	2	5	44	33	1.6	156	98	144
16	H	8.8	583	105	12	13	10	5	7	335	19	41	166	33	4554	4	3	66	103	0.4	340	73	280
17	M	8.7	592	19	24	20	59	2	7	363	24	13	28	13	1090	1	0	35	7	4.4	320	330	337
18	E	9.2	1873	210	8	49	179	17	295	791	148	27	61	7	2298	2	7	151	7	4.8	1293	756	895
19	E	8.9	1007	108	11	29	99	16	93	527	91	44	35	16	2540	3	5	47	5	3	683	405	584
20	E	8.9	718	79	27	16	41	12	75	323	30	21	110	57	2130	2	0	149	33	2	440	199	315
21	E	8.8	708	61	21	15	52	8	73	355	26	16	24	9	1227	3	23	21	6	3	415	281	335
22	M	8.8	546	36	25	12	37	4	43	280	21	16	27	7	1242	1	5	6	23	1.5	317	228	266
23	H	8.6	328	19	32	11	10	4	13	173	8	16	166	117	3138	2	4	28	35	2.1	176	123	155
24	H	8.6	362	10	37	9	13	8	49	113	14	22	155	59	0	3	16	84	77	1	191	146	108
25	M	9	844	60	21	20	71	8	109	361	39	28	28	12	1868	2	5	22	8	2.8	511	348	360
26	M	9	779	45	18	18	75	6	89	360	42	25	25	10	1588	2	5	17	5	2.9	493	354	364
27	H	8.7	498	35	25	13	28	17	25	227	13	13	108	57	1384	1	22	75	41	2	280	185	207
28	E	9	1721	210	7	35	152	30	213	707	168	30	50	20	2191	2	3	27	9	1.4	714	427	859
29	E	9	411	20	19	19	24	3	20	202	23	20	79	25	2140	2	4	29	46	2.2	227	146	203
30	E	8.9	547	53	23	14	31	4	23	344	18	21	45	26	1844	2	5	36	21	1.9	349	190	283
31	E	9.1	1150	129	10	13	108	16	60	617	89	27	33	17	1585	2	5	33	6	3.5	728	467	654
32	E	8.8	467	33	24	10	41	3	11	337	26	12	46	14	1090	1	2	33	22	2.5	327	239	305
33	E	7	871	100	26	17	48	21	138	330	27	18	47	14	1623	2	7	24	26	2.3	536	206	315
34	E	8.8	1001	68	20	13	91	5	215	362	24	14	30	10	1140	1	10	20	6	3.5	615	424	338
35	E	8.5	271	10	35	2	10	1	4	164	35	19	127	81	1280	1	19	88	33	2.5	149	129	147
36	M	8.3	269	3	29	5	12	1	3	149	5	14	28	12	933	1	4	26	10	3.7	136	120	127
37	M	8.2	245	5	31	5	12	1	3	147	16	14	24	9	833	1	5	15	7	3.4	140	116	135
38	M	8.7	717	88	15	7	40	20	18	386	19	15	26	11	1049	1	2	25	8	3	400	201	348
39	M	8.8	799	99	18	9	47	28	29	443	43	22	24	9	1329	1	8	33	6	2.7	486	238	392
40	H	8.1	374	21	29	3	23	2	4	246	5	12	66	21	1273	1	10	87	25	2	207	168	210
41	M	8.3	300	14	27	3	15	3	4	188	4	11	25	10	720	1	2	2	8	3.1	163	126	160
42	M	8.2	256	6	33	2	13	1	2	160	2	10	15	5	726	1	3	12	4	3.9	140	126	151
43	E	8.7	333	14	26	8	19	3	5	208	11	14	39	11	1207	1	4	23	17	1.8	181	143	197
44	E	8.4	295	18	31	4	14	2	14	185	7	0	40	11	1001	1	9	8	16	1.8	220	140	164
45	E	8.8	299	18	30	4	14	2	14	187	4	0	39	10	1010	1	6	10	14	1.8	221	144	159
46	M	8.6	318	13	23	9	19	2	5	198	10	15	35	11	1179	1	3	22	10	2.5	172	135	179
47	E	8.3	300	12	30	2	16	1	3	184	5	13	22	8	911	1	6	25	5	3.2	158	138	159
48	E	8.6	467	16	33	11	28	1	44	228	10	15	45	14	1434	1	12	3	18	2.4	227	183	201
49	M	8.4	268	8	31	3	12	0	2	167	4	36	19	5	761	1	8	17	4	4.9	158	128	144
50	H	8.4	286	12	32	2	11	3	6	165	4	10	108	64	824	1	20	31	30	2.4	153	127	142

M—Mesotrophic; E—eutrophic; H—hyper-eutrophic.

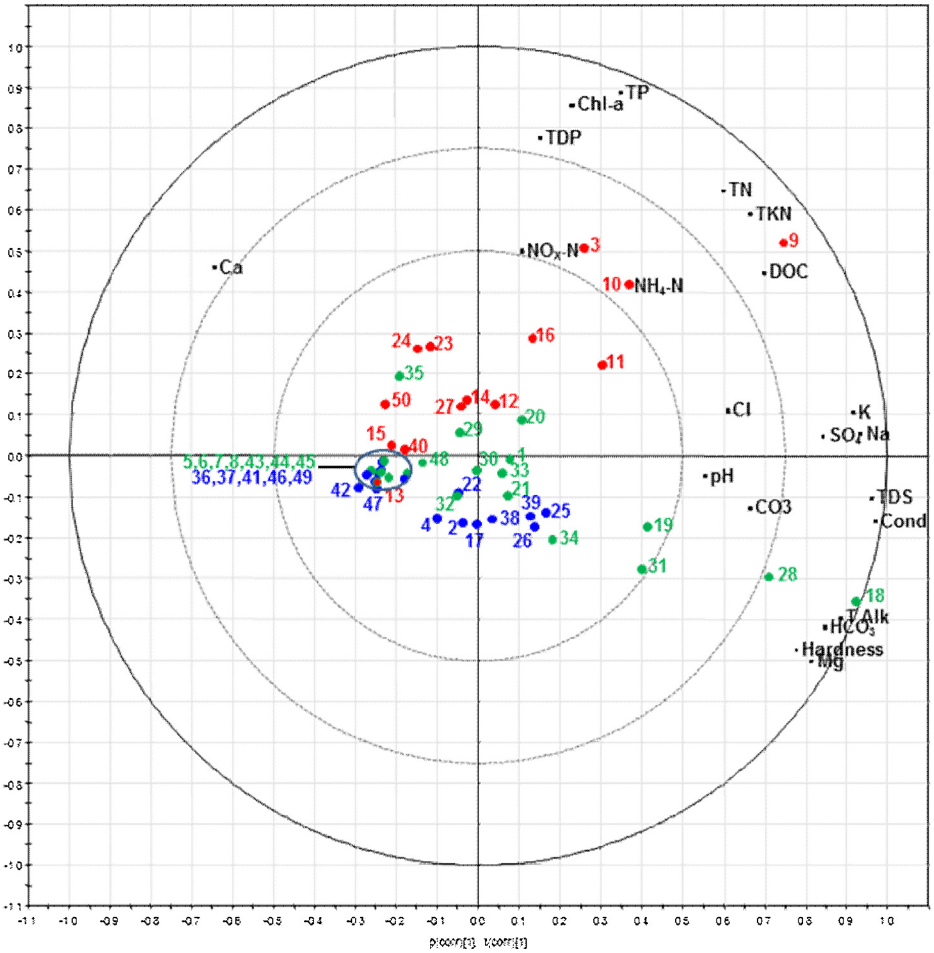

Fig. 3. PCA biplot showing similarity between lakes in relation to the major geochemical drivers. Lakes numbers are identified in Table 1. Proximity of points to each other is indicative of similarity in geochemical parameters. Proximity to the origin indicates similarity to average conditions for the entire dataset. Trophic status is colour-coded, where blue is mesotrophic, green is eutrophic and red is hyper-eutrophic.

In general, this is an evaporative region with low runoff. In Table 1, some negative values are computed for water yield, coinciding with evaporation/inflow (E/I) ratios greater than 100 %. This suggests an imbalance in the lakes due to more than 100 % of inflow being evaporated. These are systems that appear to be actively drying, at least in the short-term (i.e. Cooking Lake, Sandy Lake North, Sandy Lake South, George Lake, and Upper Mann Lake). Repeat sampling of the lakes over time may allow for a re-assessment of this trend in future. Some lakes also appear to be relatively tolerant to drought, primarily those with runoff in excess of the precipitation-evaporation deficit. Some of the more drought resistant lakes, with over 30 mm·year^{-1} of estimated runoff, include Sylvan Lake, Battle Lake, Pigeon Lake, Wizard Lake North, Wizard Lake South, Muriel Lake, Bear Trap Lake, Goose Lake, Crane Lake, Marie Lake, Touchwood Lake, and Lac La Biche.

Average residence time is estimated at 11 years, with individual lakes ranging from 2.3 years to more than 50 years. Below average residence times are typically noted for lakes that are currently experiencing drought; the exception being Upper Mann Lake which has a residence time of 37 years. The effect of short-term drought in some lake systems (those with less than 30 mm/year of runoff) is likely buffered by longer residence times (e.g. Minnie Lake, Skeleton Lake North, Skeleton Lake South, Amisk Lake, Amisk Lake South, Wolf Lake, and Beaver Lake). Taken together, water residence times and water yield appear to be valuable indicators of the drought tolerance of the lakes.

3.5. *Physical water balance drivers*

If physical characteristics of the basins are also considered, a more complete picture of the water balance effects emerge. A PCA biplot is shown for lakes, including scores of the individual lakes and loading of watershed parameters, where lakes are differentiated by both trophic status and water level status (Fig. 4). The plot reveals four distinct categories of lakes roughly corresponding to the four quadrants of the PCA plot:

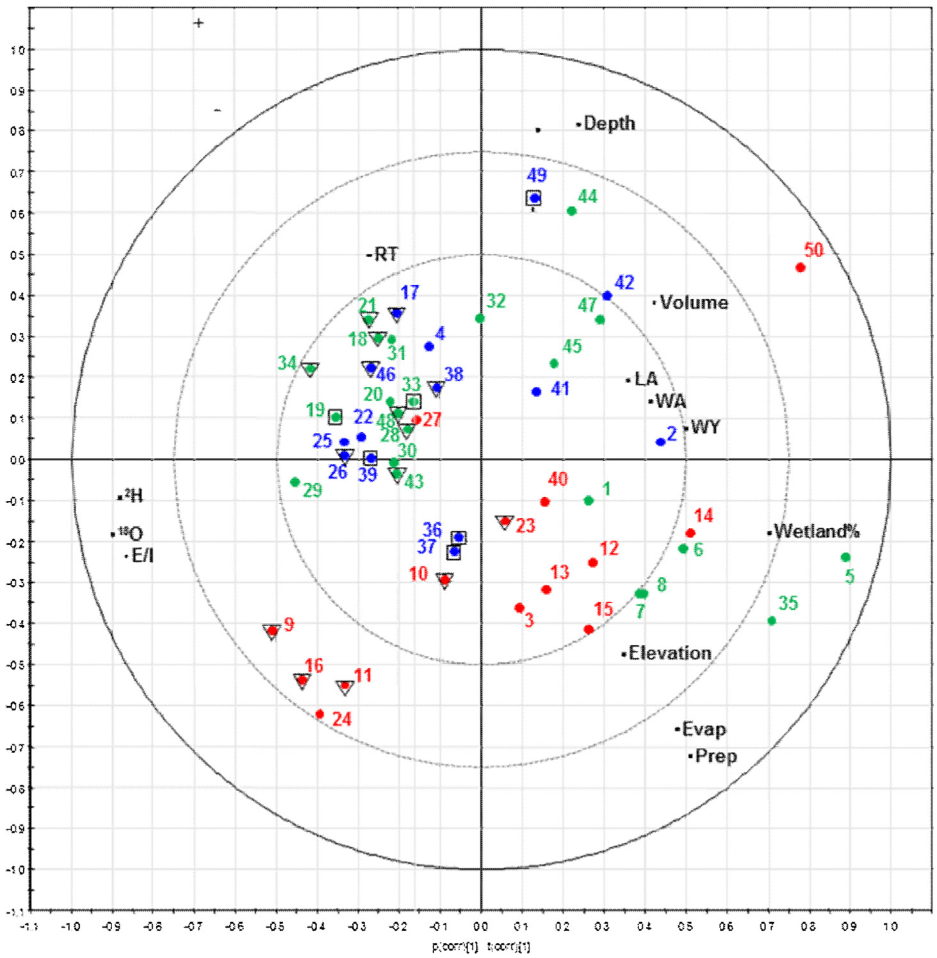

Fig. 4. PCA biplot showing similarity between lakes in relation to the major physical drivers. Lake numbers are identified in Table 1. Proximity of points to each other is indicative of similarity in physical parameters. Proximity to the origin indicates similarity to average conditions for the entire dataset. Trophic status is colour-coded, where blue is mesotrophic, green is eutrophic and red is hyper-eutrophic. Water level status is also shown, where square outlines indicate increasing water levels and triangles indicate decreasing water levels. Lakes that are not outlined have relatively stable water levels.

(i) (Upper right quadrant) Deep or large volume parkland/boreal lakes with high water yield: These lakes have low *E*/*I*, high water yield, generally stable water levels, and mesotrophic or eutrophic status. Lac La Biche is the only lake in this group that shows hyper-eutrophic status, which may be due to the town of Lac La Biche discharging its treated sewage into the lake. Residence times are intermediate due to the combination of higher volume and higher rates of flushing. Elevations are intermediate. This group includes Sylvan L., Ethel L., Marie L., Amisk L., Amisk L. N., Wolf L., Touchwood L., Lac La Biche. Note that the water balance at Sylvan Lake is largely artificial, reflecting the effect of periodic diversions from a nearby river.

(ii) (Lower right quadrant) Prairie lakes with high water yield: Shallower lakes with low *E*/*I*, high water yield, and short residence times, with abundant wetlands. Lake levels are relatively stable, elevations and evaporation rates are slightly higher than average. These lakes have relatively short residence times and tend to be hyper-eutrophic, or eutrophic where inflows are amplified. This group includes Pine L., Blackfalds L., Battle L., Pigeon L. Wizard L W., Wizard L. E., Big L., Lac St. Anne E., Lac St. Anne W., Devils L., Goose L. and Tucker L.

(iii) (Lower left quadrant) Prairie lakes with low water yield: These are shallow, small volume lakes with low or negative water yields, and unstable (usually declining) water levels. Lakes tend to be at intermediate elevations and are hyper-eutrophic except where spring-fed (Long Island L.N, Long Island L. S.). Residence times are intermediate. This group also includes Cooking L., Hastings L., Sandy L. S., Sandy L. N., George L., and Lac La Nonne.

(iv) (Upper left quadrant) parkland/boreal lakes with low water yield: Intermediate depth, intermediate volume lakes distinguished by low water yield and longer residence times. Lakes are situated at lower elevations and are likely better connected to groundwater sources. Watersheds are typically small and flushing is subdued. Lake levels are stable to variable, either increasing or decreasing. Greater than 50 % of these lakes are mesotrophic and only 1 is hyper-eutrophic (Kehewin L.). Several of the eutrophic lakes appear to have saline water inputs as noted in discussion of Fig. 3 (Lac

Table 3
Generalized characteristics of lakes by category.

Category	Description	E/I	W_Y	Residence time	Depth	Elevation	Water levels	Trophic status	Comments
High runoff systems									
1	Large parkland/boreal lakes	Low	High	Interm	Deep	Interm	Stable	M or E	Large watersheds, often forested, surface water dominated or glacial channels
2	Prairie lakes	Low	High	Short	Shallow	High	Stable	H or E	Surface water dominated or glacial channels, sloping bottoms, wetlands, variable development
Low runoff systems									
3	Prairie lakes	High	Low	Interm	Often shallow	Interm	Declining	H	Surface water dominated, sloping bottoms, some spring fed, often highly developed
4	Parkland/boreal lakes	High	Low	Long	Deep	Low	Variable, some increasing	M or E	Smaller watersheds, often forested, steep sided, strong groundwater connections

Santé, Laurier L. Muriel L., Bear Trap L. and Minnie L.). High conductivity and high sulfate may help to keep algae and cyanobacteria in check in these lakes (Lakewatch, 2012). This group also includes Clear L., Lac Bellevue, Stoney L., Frog L., Fishing L., Bluet L., Garnier L. N., Upper Mann L., Mons L., Bear Trap L., Moose L., Crane L., Hilda L., Skeleton L. N., and Beaver L.

It is important to note in Fig. 4 that the right quadrants, both upper and lower, are dominated by lakes with stable water levels, whereas the left quadrants, both upper and lower, contain most of the lakes with changing water levels, although some are also stable. This likely reflects the impact of the loading of water yield and E/I. The bottom quadrants, both right and left contain the prairie lakes, which are typically shallow with sloping bottoms. The upper quadrants, both left and right contain parkland/boreal lakes that are generally deeper with steeper sides. Important patterns are also noted for trophic status in the various quadrants. This is used as the basis for a classification scheme for the lakes, as discussed below.

4. Discussion

Stable isotope mass balance, as shown, provides a first-approximation of important water balance quantities such as the flushing rate of the lakes, captured by evaporation/inflow (E/I), and the runoff to the lakes, captured by the water yield (W_Y) estimates. E/I, which ranged between 18 and greater than 100 % was higher on average than the range estimated by Bennett et al. (2008) of 8–71 % for 50 Boreal lakes in northern Alberta, the latter values confirmed for longer periods in the same lakes by Gibson et al. (2010a,b, 2015a). A wider range in E/I including values greater than 3 have been reported for northern deltas where lakes vary from being well-connected to river channels to intermittently flooded (Brock et al., 2009; Wolfe et al., 2012). Bennett et al. (2008) demonstrated that water yield estimates to lakes were comparable to runoff estimated based on river discharge data for boreal forested watersheds. Gibson et al. (2015a,b) determined that some lakes had even higher water yields due to contributions from melting permafrost, which is not a factor influencing the lakes in this study. While the upper limit of water yield approached riverine runoff in the area, the most distinctive finding is that that water yield was occasionally predicted to be negative for some lakes. This arises particularly in cases where lakes are actively drying.

Our analysis also uses these isotope-based indicators to refine estimates of residence time that were previously based upon spatially or temporally incomplete inflow estimates to the lakes. While absolute quantities need to be interpreted with caution, especially for lakes with unstable water levels, the isotope-based approach remains a robust method for first-approximation of regional trends, and for comparison and classification. Multi-year residence times, ranging from 2.3 to 58 years, likely promotes inter-annual stability in the isotopic composition of lakes, and allows for estimation of meaningful long-term water budgets. This would not be possible if residence times were less than a year or so. Based upon the PCA analysis of the physical lake and watershed parameters (Fig. 4) including isotope based estimates of water balance, we propose a general classification scheme for lakes (Table 3). Four classifications are proposed, roughly corresponding to the four quadrants shown in Fig. 4, including parkland/boreal lakes with high and low water yield or runoff, and prairie lakes with high and low water yield.

One of the main findings of the isotope-based assessment is that water yield appears to be the primary determinant of water level stability. Lake basins with abundant runoff tend to maintain close to constant volume over decadal time scales whereas lakes with low runoff are evidently more susceptible to drought. In a few cases, water levels are also observed to be on the increase although such examples are fairly limited (see Table 1). Note that water yield estimated from this analysis is a combination of surface water and groundwater inflow, so we are unable to say directly which is the dominant source, although geochemistry and field-based observation help in many cases to identify if groundwater is more influential. We find that shallow prairie lakes with low water yield appear in many cases to be drying, and are either eutrophic or hyper-eutrophic unless spring-fed. It appears that evaporation is important to the accumulation and concentration of nutrients in these systems. We also find that deeper boreal/parkland lakes tend to be healthier (i.e. mesotrophic or low-level eutrophic) especially if they have low water yield and therefore longer residence times. High conductivity and sulfate, apparently associated with saline groundwater inputs, also appear to limit algal and cyanobacterial growth, promoting healthier conditions.

van der Kamp et al. (2008) showed that many closed-basin lakes across the prairies have experienced water level decline since the 1920s, and that this pattern holds from south-central and east-central Alberta though central and southeast Saskatchewan. They concluded that changes were climatically-driven but also reflected the influence of land-use changes due to agriculture. While our analysis does not specifically characterize or quantify the extent of development in the watersheds, we suggest that this would be an important area for follow-up analysis. Our study expands beyond drying systems and provides some context for understanding the characteristics of lakes that make them susceptible to drought. This includes low runoff, slow flushing (i.e. high E/I ratios), lack of wetlands, shallow depth, and sloping bottoms. It is important also to note that sustained drought due to regional warming may eventually impact more of the healthier lakes in central Alberta which appear to be buffered at the present time by long water residence times. We emphasize that many prairie lakes such as Lake Winnipeg and Lake Manitoba have not experienced contemporary water level decline, although response in these systems has also been buffered by long residence times in some sub-basins (e.g. South Basin, Lake Manitoba), by open system conditions, by regulation, and by their geographical position, being situated farther to the east.

5. Conclusions and future recommendations

This study has provided water balance information, including water yield, evaporation/inflow ratios and residence time estimates for 50 lakes in central Alberta based on a stable isotope mass balance method. Water yield was found to range from near zero to 235 mm·year^{-1}, evaporation/inflow ratios were found to range from 18 to 136%, and water residence time ranged from 2.3 to 58 years. Important physical and geochemical properties of the lakes are described, including the relationship between water balance, water level and trophic status. Four distinct lake classes are proposed, namely prairie and boreal/parkland lakes with both high and low water yield. Water level stability is shown to depend strongly on the water yield to lakes and percentage of wetland in the catchment. The healthiest lakes in terms of trophic status were medium to deep lakes with smaller catchments that have longer than average residence times. These lakes may have stable, increasing or decreasing water levels. The most distressed lakes in terms of trophic status and water level were shallow prairie lakes with limited water yield.

While our analysis is based on use of indicators from a one-time isotope-based assessment compared with long-term chemistry, we find this a promising first-approximation approach for establishing water quality–water quantity relationships for lakes in the region. In the future, we plan to extend temporal monitoring of the isotopic composition of lakes and isotope-based water balance which may be particularly helpful for tracking site-specific and regional changes. Complementary information on the groundwater contribution to water yield might also be obtained by conducting a systematic radon-222 survey of the lakes similar to the approach demonstrated by Schmidt et al. (2010). Radon is a radioactive gas with a short residence time that is only found in lakes with active groundwater connections. Further assessment of the relationship between agricultural development, oil and gas development, and nutrient, water balance and water level status in the lakes is also urgently needed to mitigate future environmental degradation. Isotope-based techniques are expected to be helpful for regional characterization of spatio-temporal hydrologic responses in lakes.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2016.01.034.

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