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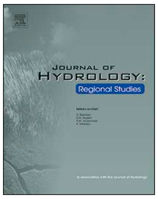

Isotopic tracing of hydrologic drivers including permafrost thaw status for lakes across Northeastern Alberta, Canada: A 16-year, 50-lake assessment

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ABSTRACT

Study region: Surveys of stable isotopes of water in 50 boreal lakes were conducted during 2002–2017 as a component of Alberta's Oil Sands acid sensitivity program in northeastern Alberta.

Study focus: Using an isotope mass balance approach, watershed, climatic and isotopic data were applied to estimate evaporation losses and residence time of lakes, as well as to estimate water yield from watersheds.

New hydrological insights for the region: Site-specific differences in water yield to 50 lakes over 16 years were found to be controlled by latitudinal gradients in climate, wetland type, lake/watershed configuration and permafrost. 19 plateau watersheds located northeast of Fort McMurray and in the Birch and Caribou Mountains which contained significant permafrost were found to have similar water yield to permafrost-poor watersheds if fen-dominated (159 mm/yr: n = 5 vs. 166 mm/yr; n = 31), and enhanced water yield (405 mm/yr; n = 14) if bog-dominated. Water yield was found to be systematically dependent on permafrost extent, yielding up to several hundred millimetres of additional runoff in bog-dominated systems. Temporal trend analysis indicates systemic momentum of change in hydrologic drivers over the 16-year period, although few are statistically significant. A new conceptual framework is proposed for classification of site-to-site permafrost thaw stage to improve water yield prediction, which is expected to influence lake water quality including observed pH increases noted previously for many lakes in the region.

1. Introduction

Isotope mass balance (IMB) methods have been widely applied to characterize water balance in surveys across Canada (Arnoux et al., 2017a, b,Arnoux et al., 2017cc; Brock et al., 2009; Wolfe et al., 2011; Turner et al., 2014; Yi et al., 2008; Gibson and Reid, 2010, 2014; Gibson et al., 1993, 2016a, 2017), across the contiguous United States (Brooks et al., 2014), along joint international waterways such as the Great Lakes (Jasechko et al., 2014), and worldwide (e.g. Petermann et al., 2018; Vystavna et al., 2018; Wan et al., 2019a). Regional assessments have been carried out periodically in the oil sands region, northeastern Alberta (Prepas et al., 2001; Bennett et al., 2008; Gibson et al., 2002, 2010a, 2015a, 2019a,b) and across western Canada in support of assessments of

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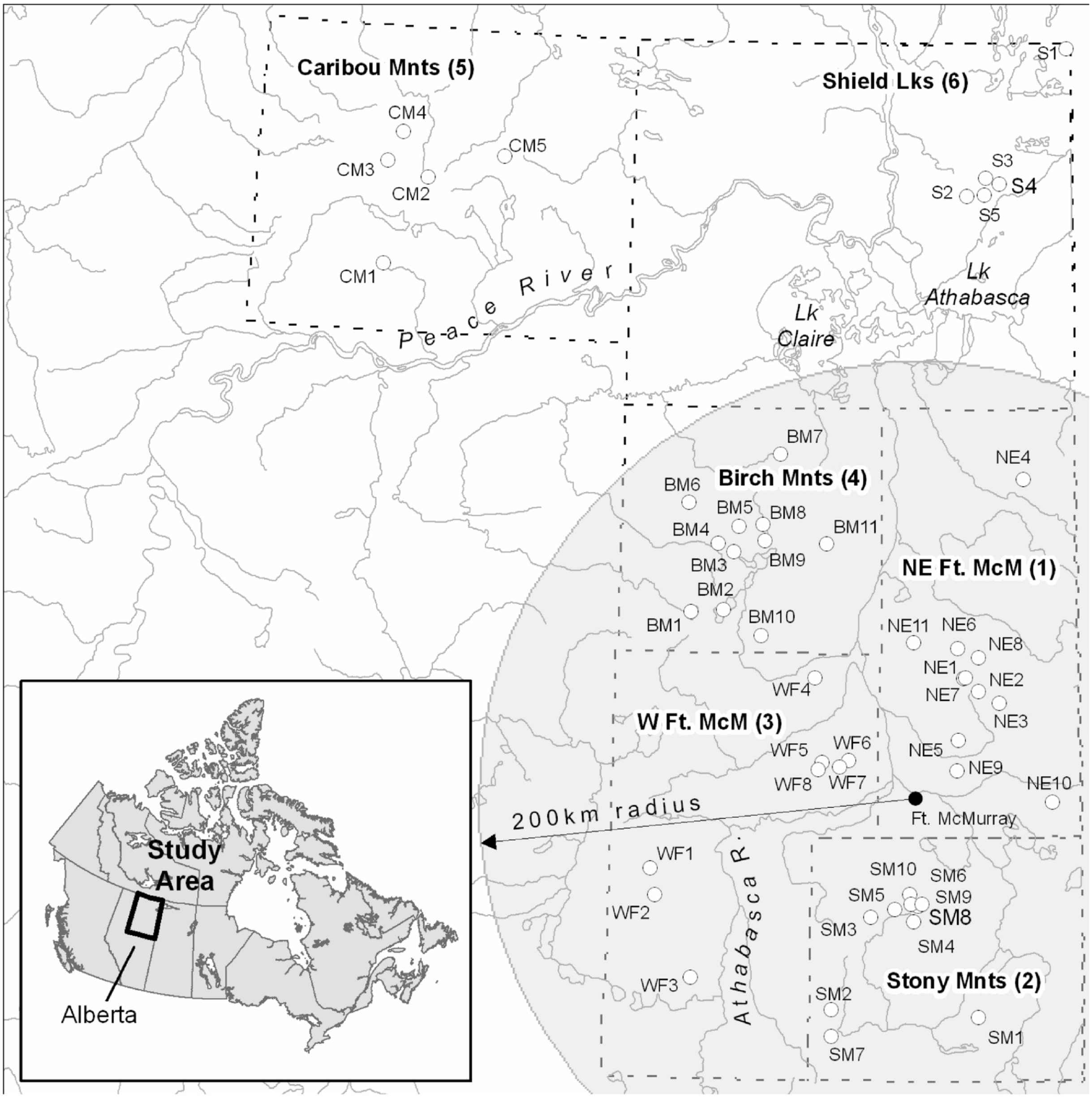


Fig. 1. Map showing the location of study lakes relative to the city of Fort McMurray (Gibson et al. 2015b).

acidifying sulfur and nitrogen deposition in ungauged or under-monitored regions (Scott et al., 2010; Jeffries et al., 2010; Gibson et al., 2010b, 2018). The critical loads approach, applied to map sensitivity of lakes and watersheds to deposition of acidifying sulfur and nitrogen, is based on the hypothesis that lake acidification is buffered by base cation weathering in the catchment, and therefore predicts that acidification should be be dependent upon both the water yield to lakes (a.k.a. watershed runoff) and the runoff/lake water chemistry (see Henriksen et al., 1992). Importantly, critical loads mapping and monitoring in the oil sands region has been applied to assess risk and to serve as an early warning indicator of potential deposition impacts from oil sands emissions including pH decrease in lakes and ecosystems (Cathart et al., 2016). This and other major health and environmental concerns related to oil sands development have captured widening public interest in Canada and worldwide (Gosselin et al., 2010).

From 1998–2017, a regional network of 50 representative lakes have been sampled and analyzed annually in the oil sands region under various programs including the Regional Aquatic Monitoring Program (RAMP), Joint Oil Sands Monitoring (JOSM), and Oil Sands Monitoring (OSM), as a means to ascertain potential for lake acidification given relative proximity to oil sands mining operations (Fig. 1). Stable isotopes of water (oxygen-18 and deuterium) have been routinely incorporated within the monitoring program since 2002 to provide water balance control as the lakes are remote and impractical to gauge using conventional methods. While the lakes were carefully monitored to detect potential for pH decrease, many of the lakes have in fact undergone a significant increase in pH over the past two decades (Gibson et al., 2019c). Several hypotheses, possibly triggered by climate changes, including lake eutrophication, changes in permafrost status, and/or alteration of surface/groundwater flowpaths in the lake-watershed systems can be postulated as potential causes, although as yet no clear evidence of a specific cause has been established. The objectives of this paper are: (i) to provide a water balance assessment of the 50 lakes over a 16-year period (2002–2017) including evaporation loss and water yield, (ii) to spatially evaluate the major hydrologic drivers (i.e. climate, land cover, permafrost) across the region including differences between various lake sub-groups, (iii) to assess temporal changes in water balance indicators and to identify major drivers of these hydrologic changes, and (iv) to evaluate potential water balance – water quality linkages including pH increase in lakes. Our study assists in developing a better understanding of the relationship between runoff, permafrost thaw and potential causes of pH increase in large numbers of lakes across northeastern Alberta.

This study leverages insight gained from a previous nine-year IMB assessment of the RAMP lakes (2002–2010; Gibson et al., 2015a) and significant previous investigations of boreal plains hydrology and hydrogeology (e.g. Prepas et al., 2001; Gibson et al., 2002; Devito et al., 2005; Smerdon et al., 2005). While characteristics such as bog cover, permafrost extent, and presence/absence of thaw scars in bogs were previously assessed by Gibson et al. (2015a) and found to be important hydrologic drivers, morphometric properties such as lake elevation, lake area, and drainage basin area were also found to be hydrologically influential. Although permafrost and permafrost meltwater were found to be indistinguishable from modern precipitation based on oxygen and hydrogen stable isotope composition, IMB calculations suggested that thaw contributions of up to several hundred millimetres of runoff per year were occurring in 14 of the 50 lake watersheds (Gibson et al., 2015a). This observation was further supported by measurement of higher tritium content in such lakes (deemed thaw lakes) compared to a subset of other lakes in the area, which was attributed to water sources derived from thawing of post-1950s permafrost (Gibson et al., 2016b). IMB has also been used to interpret and map evaporation loss and water yield in a survey of 121 lakes across 28,000 km^2 in the South Athabasca Oil Sands (SAOS) area (comparable to Stony Mountains (SM) area used in this study), and demonstrated consistent spatial patterns overprinted by slight interannual variability in 3 consecutive years (2007–2009). Importantly, that assessment demonstrated spatial autocorrelation of derived water balance characteristics, and reasonable agreement between isotope-based and gauged estimates of water yield (Gibson et al., 2019b). Higher water yields were generally found for lakes on peat plateaus such as the Stony Mountains (SM), Birch Mountains (BM) and Caribou Mountains (CM) due to presence of impermeable Colorado Group shale substrates and extensive bog cover.

2. Study sites

As summarized in Gibson et al. (2015a), the study lakes are situated in boreal plains and boreal shield regions of northeastern Alberta (Fig. 1). Forty of the study watersheds are located within 200 km of Fort McMurray, which lies close to the centre of current Alberta oil sands operations. Ten sites are situated in the Stony Mountains (SM), eight west of Fort McMurray (WF), eleven northeast of Fort McMurray (NE), and eleven in the Birch Moun-tains (BM). An additional ten lakes are located north of oil sands operations; five in the Caribou Mountains (CM), and five north of Lake Athabasca (S). The sites in each sub-region span a typical range in elevation, land cover, and hydrogeologic setting, and are broadly representative of each area. Lakes range in size from small, shallow lakes (1 m-depth, $< 0.5 km^2$) to large lakes (30 m-depth; 0.43 km^2; Gibson et al., 2015a). Watersheds draining to the study lakes typically contain less than 3 % open water and so are considered to be headwater catchments. Watersheds are also wetland-dominated (Prepas et al., 2001) with bogs and fens often being most abundant in plateaus and lowlands, respectively. Upland forests are mostly restricted to banks of well-drained, incised stream channels. Permanent streams rarely occur upstream of lakes but rather tend to form as drainage channels from lake outlets (Gibson et al., 2015a). While shield lakes north of Lake Athabasca (S) are underlain by relatively impermeable Canadian Shield rocks mantled by thin, discontinuous Quaternary deposits, comparably impervious Colorado Group shale substrates underlie plateaus (SM, BM, CM) forming a shallow, relatively impervious barrier to vertical groundwater movement. More permeable substrates are typically found in lowland areas where bedrock consists of sandstone, siltstone, shale and carbonates of Cretaceous to Devonian age. Buried Quaternary channels are a common feature of the region and, as with stream channels, are locally influential as sources and/or sinks of water in some area lakes (Gibson et al., 2019b). While buried channels may be regionally influential, none of the study lakes are known to be in direct communication with buried channels.

Permafrost terrain, which is currently unstable and in disequilibrium with the current climate, plays an influential role in hydrologic conditions across the region (Vitt et al., 1999). Many bogs in northeastern Alberta contain small, isolated internal wet depressions, collapse scars or internal lawns, usually interpreted as thaw features. While permafrost is mainly confined to treed bogs situated on plateaus, six fen-dominated plateau watersheds also contained both open and treed fens with significant permafrost (5–9%). A summary of the study lake/watershed characteristics by lake sub-regions is provided in Fig. 2. Additional statistics and site descriptions are provided in the accompanying Data in Brief article Gibson et al. (2019d). Additional discussion of the study sites was provided by Gibson et al. (2015a).

3. Method

3.1. Water sampling and analysis

Water samples were collected from float plane or helicopter in 30-mL to 1-L high-density polyethylene bottles with tightly-sealed polypropylene lids, which have been shown to be very effective at preventing evaporative isotopic fractionation for periods in excess of one year (Spangenberg, 2012). Procedures for sampling groundwater, permafrost, and permafrost meltwater for isotopic analysis

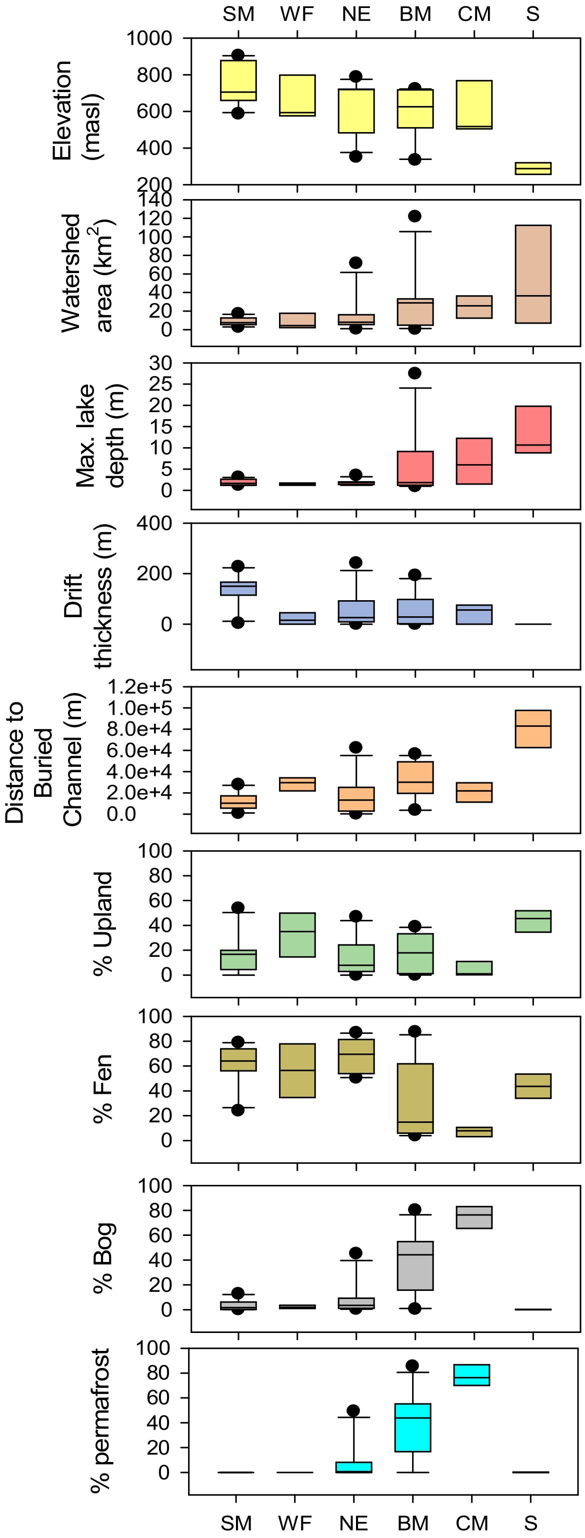


Fig. 2. Box plots showing selected characteristics of study lakes/watersheds by regional sub-groups ordered from south to north: SM -Stony Mountains, WF-West Fort McMurray, NE-Northeast Fort McMurray, BM-Birch Mountains, CM-Caribou Mountains, S – Shield. Number of sites is as follows: SM (n = 10),WF (n = 8), NE (n = 11), BM (n = 11), CM (n = 5),S (n = 5).

followed standard field methods as described previously by Gibson et al. (2015a). Water sampling procedures for lakes have been described in detail previously (Gibson et al., 2010a, b; Gibson et al., 2015a, [Gibson et al.,2015b]b). In general grab samples of water were collected at 1-m depth from lake centre locations during late August to early October when lakes are typically well-mixed and vertically unstratified, which has been shown in previous Alberta lake surveys to provide representative samples for isotope mass balance analysis (Gibson et al., 2002). Stratification, if present, is expected to have led to enrichment of the epilimnion compared to the hypolimnion due to direct exposure to evaporation, the latter of which also potentially has higher rates of groundwater exchange. Given the sampling strategy, we would expect bias in stratified systems to favour sampling of the epilimnion, thus leading to more enriched isotopic values being used in our analysis as compared to a representative average based on whole lake sampling. In this case, the IMB analysis would predict lower water yields, and so is likely to be conservative in terms of evaluating the magnitude of runoff, including permafrost meltwater impacts. A previous analysis of stratification effects on IMB applied in the Turkey Lakes watershed, Ontario, Canada, illustrated that near surface grab sampling of a deep lake, Turkey Lake (32 m) and a shallower lake, Little Turkey Lake (13 m) led to underestimation of water yield by 18 % and 6 %, respectively, as compared to whole lake sampling (Gibson et al., 2017), which we regard as a useful upper limit for uncertainty in applying the method to deep lakes.

Stable isotope results for ^{18}O and ^{2}H are reported in δ notation in permil (‰) relative to Vienna Standard Mean Ocean Water (V-SMOW) on a normalized SMOW-SLAP scale. Analytical uncertainty over the course of the study (2002 to present) is estimated to be less than ± 0.1‰ for δ^{18}O and ± 1‰ for δ^{2}H. Further details regarding protocols and instrumentation are provided in Gibson et al. (2019d).

3.2. Isotope mass balance

Isotope mass balance (IMB) methodology applied in this study uses the Craig-Gordon model (Craig and Gordon, 19651965) as described in several previous publications (Gibson et al., 2015a, b) with key indicators described here. Three principle water balance indicators derived from the IMB are fraction of inflowing water lost by evaporation (E/I), water yield (WY) and water residence time (τ). As noted by Gibson et al. (2015a, b), fraction of water loss by evaporation (x) is estimated based on the degree of evaporative isotopic enrichment of lake water relative to inflow:

$$x = E/I = (\delta_L - \delta_I)/(m(\delta^* - \delta_L)) \ \text{(dimensionless)} \tag{1}$$

where I and E are lake inflow and evaporation ($m^3 \cdot yr^{-1}$), respectively, δ_I and δ_L are isotopic composition of inflow and lakewater (‰), respectively, m is the enrichment slope which is mainly a function of humidity, temperature and boundary layer conditions, and δ^*, which is the limiting isotopic enrichment under local atmospheric conditions controlled mainly by m and the isotopic composition of atmospheric moisture (see Gibson et al., 2015b). Several basic assumptions we make include that the lake is well-mixed, and that the isotopic composition of precipitation is representative of inflow to the lakes. Recommended equilibrium and kinetic fractionation factors for small lakes described by Horita et al. (2008) were used to characterize liquid-vapour isotopic partitioning, and a partial liquid-vapour equilibrium model was used to estimate isotopic composition from atmospheric moisture from isotopic data defining the local meteoric water line and local evaporation line (see Gibson et al., 2015b).

Water yield (WY) is estimated using:

$$WY = (E/x - P)/WA \cdot 1000 \ \ (mm \cdot yr^{-1}) \tag{2}$$

where WA is the watershed area (m^2); $E = e \cdot LA$ and $P = p \cdot LA$; e and p representing the annual depth-equivalent of evaporation and precipitation ($m \cdot yr^{-1}$), respectively; LA is the lake area (m^2); and P is the precipitation on the lake area ($m^3 \cdot yr^{-1}$). Conceptually, water yield can be viewed as the depth of runoff from the watershed required to maintain the calculated lake inflow and E/I that cannot be accounted for by direct precipitation on the lake.

Lake water volume (V) was estimated from bathymetric surveys and then used to estimate residence time of water from:

$$\tau = V/I \ \text{ or } \ \tau = xV/E \ (yr) \tag{3}$$

Climatological parameters required to calculate the isotope mass balance (i.e. precipitation, temperature, relative humidity, evaporation and precipitation rates) were obtained by interpolation from the North American Regional Reanalysis dataset (NARR; Mesinger et al., 2006) as discussed previously in Gibson et al. (2010a, b, 2015a). Calculation of lake area (LA) and watershed area (WA) was based on ArcGIS and ArcHYDRO delineations. Wetland site types (bog, fen, open water, and uplands) as well as sub-classes which indicated permafrost cover, were delimited using 1:20,000 black and white photography (see Gibson et al., 2015a) consistent with the method of Halsey et al. (2003).

3.3. Statistical analysis

Principle component analysis (PCA) was used to assess potential relationships between site-specific hydrologic indices and climate and landscape controls. As demonstrated in Gibson et al. (2016a), PCA is a commonly used multivariate statistical technique that transforms and extracts meaningful information from large datasets with multiple variables. In this study, we use biplots, which are overlays of the scores of individual lakes, with loadings of variables such as water yield (WY), %Fen, and %Bog, to provide a statistical overview of key drivers. 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 Sigmastat for Windows 4.0 (Systat Software Inc.).

The Mann-Kendall (MK) non-parametric test (Mann, 1945; Kendall, 1975) was also used to identify trends in time series of isotopic and climate data as well as water balance outputs. Application of the method in hydrologic trend detection has been discussed in detail by Hamed (2008). We use the MK tau values to indicate the presence of a monotonic increasing or decreasing trend (i.e. positive versus negative values), and p values to gauge significance of trends. Trends are considered to be confirmed in cases where $p < 0.05$ although the strength and direction of tau values and significance of the correlations are also considered as qualitative indicators in the assessment and following discussion. MK statistics were computed using R (R Core Team, 2017).

4. Results and discussion

4.1. Stable isotope characteristics of lake water and input sources

Isotope analytical data for lakes and input sources sampled from 2002–2017 are provided in Gibson et al. (2019d) and are plotted in $\boldsymbol{\delta}^{18}$O-$\boldsymbol{\delta}^{2}$H space in Fig. 3. Lake isotope data (Fig. 3a) are shown to plot below the Global Meteoric Water Line (GMWL) of Craig (1961) and the Local Meteoric Water Line (LMWL) established at Mildred Lake (Baer et al., 2016), which is comparable to, but likely more representative as a regional locus of hydrologic inputs, than the Edmonton LMWL, which is based on Canadian Network for Isotopes in Precipitation (CNIP) data from several decades ago (Gibson et al., 2015a). Lakes are found to be grouped in tight linear clusters defining local evaporation lines (LELs; Fig. 3a,b). The multi-lake LEL established for the period 2002-2010 is found to be only slightly different than for 2011–2017, with consistent ranges in both time periods. Evaporation line (LEL) slopes fall within a narrow range between 5.20 and 5.41, averaging 5.29, with similar y-axis intercepts (δ^2H ranges from -47.29 to -50.61‰, averaging -49.21‰). For individual lakes, offset along the LEL from the LMWL is the isotopic enrichment signal applied as the basis for calculating fraction of water loss by evaporation (E/I) for each lake.

Isotopic composition of input sources including snowpack, groundwater, soilwater, and permafrost are shown to plot close to the LMWL for both Edmonton and Mildred Lake, largely reflecting modern meteoric water origins (Fig. 3b). Snowpack is revealed to be systematically depleted in heavy isotopes relative to groundwater, the latter sampled in industrial wells from a range of local aquifers and bedrock formations (Gibson et al., 2015a). Presence of glaciogenic waters in some groundwaters is indicated by depleted isotopic compositions (Birks et al., 2018, 2019). Soilwater, obtained through azeotrophic distillation of soil samples collected in sealed, double ziplock bags from shallow pits, is shown to span the range from groundwaters to wetland surface waters, the latter being evaporatively enriched in some locations. As noted by Gibson et al. (2015a), permafrost samples have isotopic signatures indistinguishable from modern precipitation, such that direct labelling of permafrost source waters is not possible, however, meltwater contributions augment precipitation-driven runoff and are thereby quantitatively recorded in the IMB analysis of the lake.

Mean isotopic composition of precipitation δ_P for each watershed is estimated based on empirically derived relationships between latitude, elevation and isotope composition across North America (Bowen and Wilkinson, 2002). Interpolations were performed using the annual NARR climatology (Mesinger et al., 2006), and the δ^2H of monthly precipitation was calculated assuming that precipitation would follow the relationship defined by the amount-weighted Mildred Lake LMWL (Baer et al., 2016).

4.2. Temporal variations and trends in lake water isotopic composition

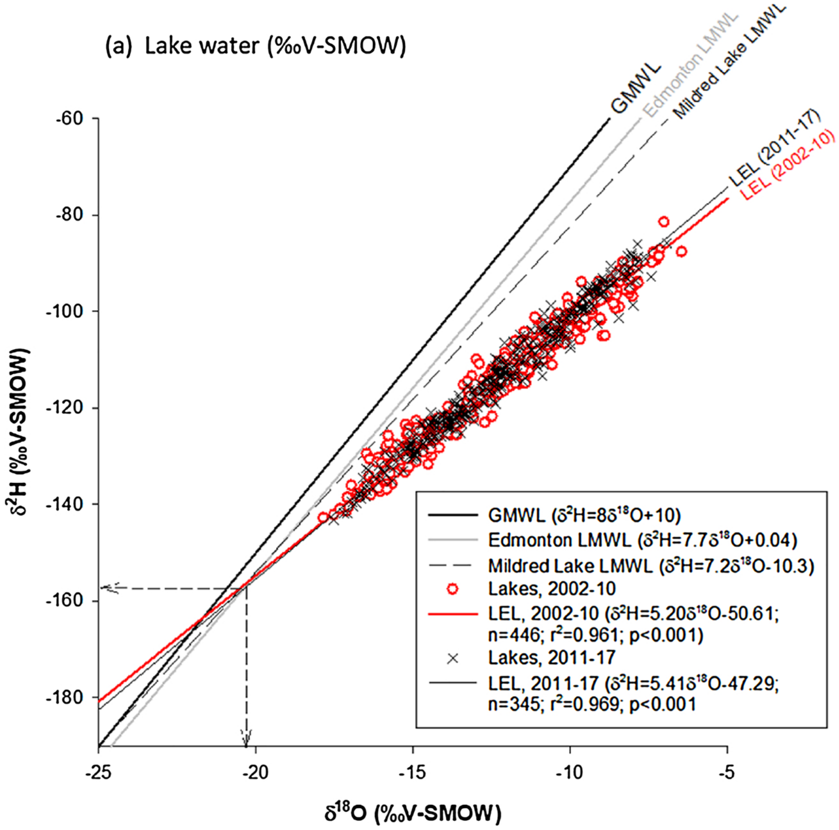
Time-series of ^{18}O isotopic composition of lakes, as grouped by lake sub-regions (Fig. 4a), illustrate regular fluctuations associated with interannual hydroclimatic variability, as well as a high degree of temporal and spatial autocorrelation, i.e. year-to-year shifts for individual lakes are systematic and regular, not random, and geographically clustered lake groups display similar responses. Positive MK tau values (see Gibson et al., 2019d) suggest upward trends in δ^{18}O in 30 of 50 lakes, although only 2 lakes, NE2 and BM7, show significant ($p < 0.05$) upward trends in δ^{18}O. Similar results are obtained for δ^2H; positive MK tau values are found in 32 of 50 lakes, although only 3 lakes (S1, S5 and BM7) show significant ($p < 0.05$) upward trends in δ^2H. Time-series isotopic data are further interpreted in the context of the IMB assessment in Section 4.4.

4.3. Temporal trends in climate parameters

Time-series of site-specific NARR climate parameters, including 2-m air temperature, 2-m relative humidity, and precipitation and evaporation at the surface are summarized by lake sub-group (Fig. 5). In general, the plots illustrate regular fluctuations associated with interannual hydroclimatic variability, as well as a high degree of temporal and spatial autocorrelation. Climate parameters appear to be similar in nearby lakes, and interannual variability appears to be more pronounced than lake-to-lake variations for the climate parameters than for δ^{18}O or δ^2H (see Fig. 4). This is characteristic of wetland-dominated landscape where spatial differences in watershed/lake hydrologic response are more dependent on watershed characteristics than on spatial climate variability, as noted in previous assessments (Gibson et al., 2010b, 2015a). Importantly, NARR climate data allows for spatial variations across the lake network to be approximated, improving the overall comparative strength of IMB across the network.

Mann-Kendall trend tests (Gibson et al., 2019d) reveal positive MK tau values for most climate parameters at most sites (260/300) although statistically significant trends are limited to only a few lakes. Notably, temperature and evaporation-flux weighted temperature was significantly upward trending for BM6, CM1, CM3, S3 and S4. Evaporation was significantly upward trending for most WF, BM and CM lakes although precipitation and humidity trends were largely insignificant. Time-series climate data are further interpreted in the context of the IMB assessment in Section 4.4.

(a) Lake water (‰V-SMOW)



(b) Input waters water (‰V-SMOW)

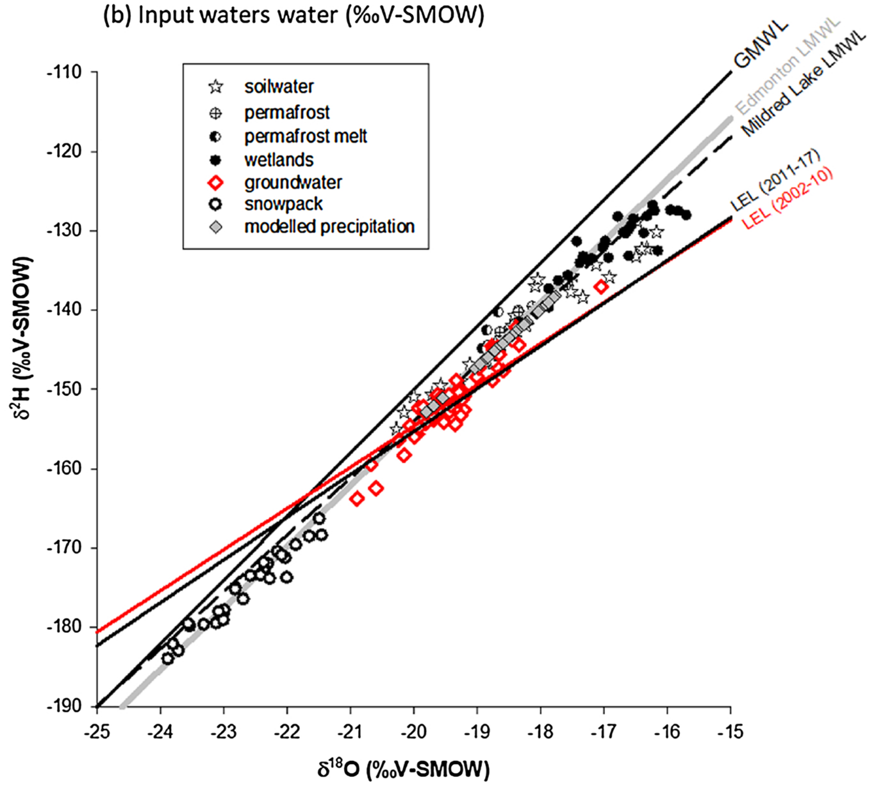


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Fig. 3. Plots of deuterium versus oxygen-18 illustrating (a) systematic isotopic enrichment of the RAMP lakes sampled during 2002–2017 compared to the Global Meteoric Water Line (GMWL) of Craig (1961), the Local Meteoric Water Line (LMWL) for Edmonton (Gibson et al., 2015a), and the amount-weighted weighted Mildred Lake LMWL (Baer et al. (2016). The Mildred Lake LMWL is likely more representative of precipitation-derived input sources to lakes within 200 km of Fort McMurray. Local evaporation lines (LELs) for 2002–2010 and 2011–2017 are provided separately to illustrate close agreement between results reported by Gibson et al. (2015a) and this update; and (b) isotopic signature of common input sources to RAMP lakes including soilwater, in-situ permafrost, permafrost meltwater in thaw scars, wetlands, groundwater, and snowpack samples. Modelled mean amount-weighted annual precipitation for lakes used in the IMB model is also shown.

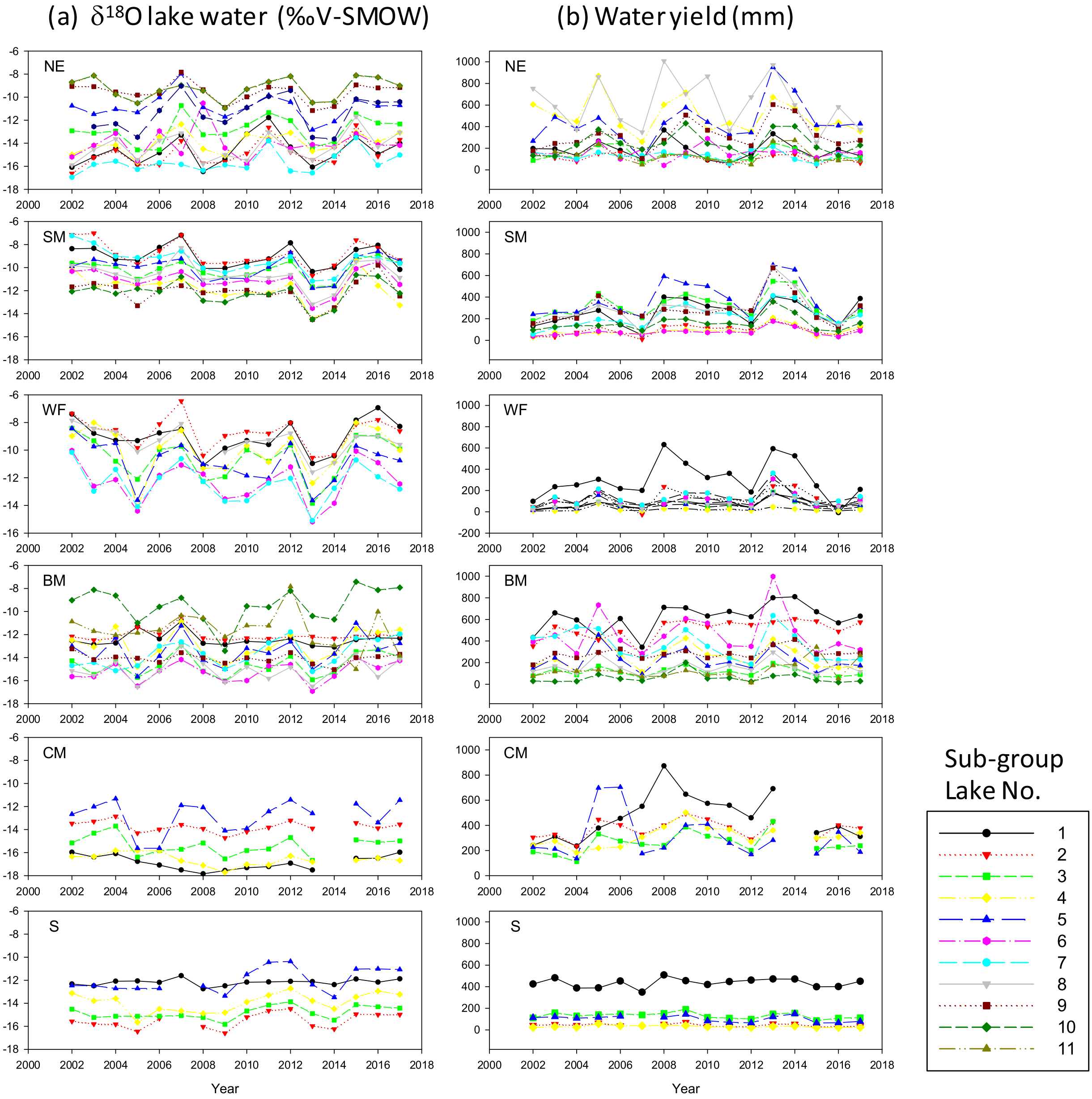

Fig. 4. Time-series of (a) oxygen-18 isotopic composition of lakes, and (b) derived-water yields, 2002–2017, sorted by lake sub-groups. Similar results were obtained for deuterium (see Gibson et al., 2019d).

4.4. Water balance indicators

Using isotopic composition of the lakes on a site-by-site, year-by-year basis, modelled values for isotopic composition of precipitation at each site, NARR climatological data, and site-specific lake/watershed characteristics, we estimate evaporation/inflow (x) from eq. (1), water yield from Eq. (2), and water residence time from Eq. (3). Complete results and trend statistics are provided in

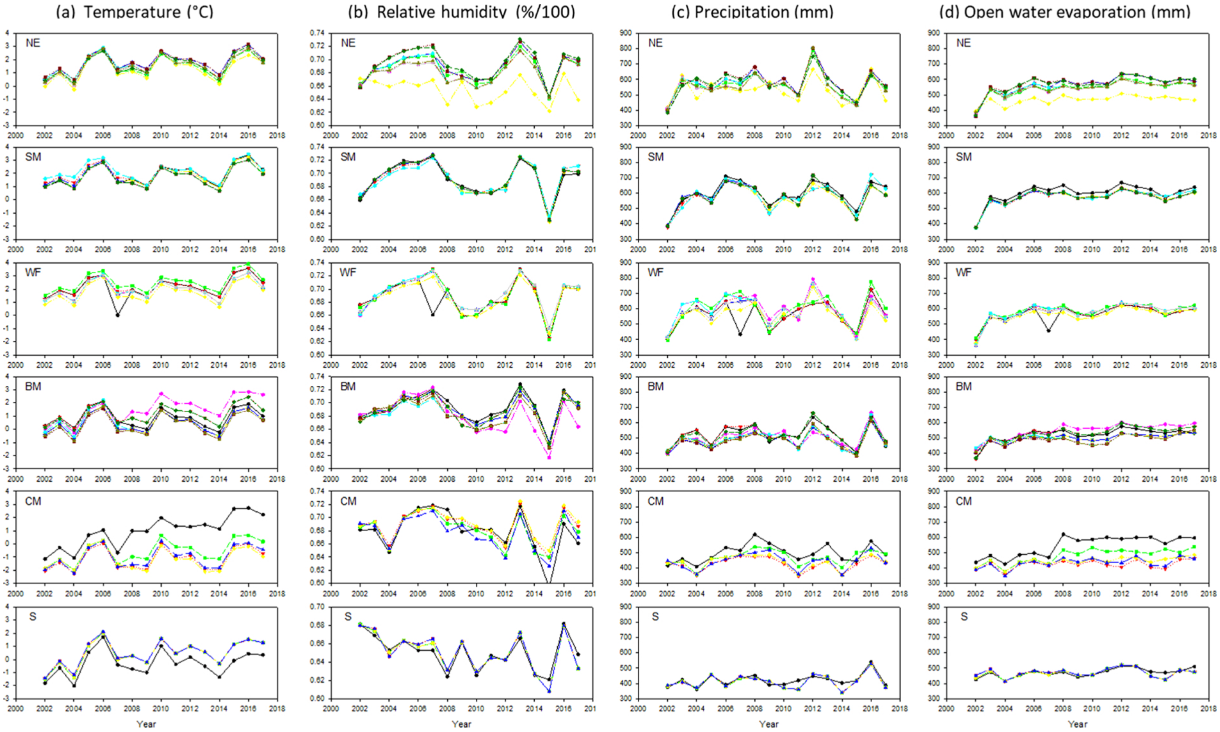

Fig. 5. Time-series of NARR climate parameters, 2002–2017, by lake sub-group: (a) mean annual 2-m air temperature, (b) evaporation-flux-weighted 2-m relative humidity, (c) annual precipitation, and (d) annual evaporation at the ground surface. See legend in Fig. 4.

Gibson et al. (2019d) and summarized by lake group in Table 1 and Figs. 4b and 6 . Note that runoff ratio was estimated as water yield depth divided by precipitation depth on the watershed area, and isotopic compositions of precipitation and atmospheric moisture were estimated in a consistent way with a previous 9-year assessment for the RAMP lakes (see Gibson et al., 2015a).

Wide ranging evaporation/inflow conditions were noted for lakes across the network, with values ranging from 4 % to 66 % of inflow, which also confirms that lakes had a reciprocal range in outflows of between 33–96% of inflow. While low flow or zero flow periods are commonly observed in summer and winter in outflow streams in the region, no such annual or interannual no-flow periods for the study lakes are indicated by the isotope balance results. We emphasize that while these results indicate that outflow likely occurred from all lakes in all monitoring years, it does not imply that the outflow was continuous, nor does it preclude that lake outflow may have become intermittent or that it may have been related mainly to spring freshet as previously noted in the region (RAMP, 2015). Evaporation/inflow for the various lake groups was found to be less than the variability across the network, with values decreasing with increasing latitude. Low permafrost systems (i.e. less than 2 % permafrost) were found to have more evaporative water balances than lakes in watersheds with significant permafrost (Table 1), suggesting higher throughputs in the latter. Water yield was found to range from 22 to 618 mm/year, with average values in the various lake sub-regions spanning from 112 to 343 mm/year (Table 1). In general, the highest water yields were found for the northern plateau lakes (NE, BM, CM) although water

Table 1

Average (minimum, maximum) evaporation/inflow, residence time, water yield and estimated runoff ratio by lake sub-region. Values for other lake groupings are also shown.

	n	E/I (%/100)	Water yield (mm/yr)	Runoff ratio (unitless)	Residence time (years)
Northeast Fort McMurray (NE)	**11**	**0.18** (0.04 to 0.46)	**270** (108 to 611)	**0.49** (0.20 to 1.10)	**0.84** (0.31 to 1.67)
Stony Mountains (SM)	**10**	**0.42** (0.24 to 0.64)	**215** (77 to 369)	**0.38** (0.13 to 0.65)	**1.14** (0.49 to 1.96)
West Fort McMurray (WF)	**8**	**0.50** (0.36 to 0.66)	**112** (22 to 302)	**0.20** (0.04 to 0.55)	**1.06** (0.61 to 1.77)
Birch Mountains (BM)	**11**	**0.23** (0.10 to 0.48)	**287** (58 to 618)	**0.58** (0.11 to 1.20)	**2.06** (0.22 to 10.81)
Caribou Mountains (CM)	**5**	**0.18** (0.11 to 0.29)	**343** (258 to 468)	**0.74** (0.54 to 0.92)	**2.41** (1.12 to 3.74)
Shield Lakes (S)	**5**	**0.19** (0.09 to 0.26)	**149** (32 to 435)	**0.36** (0.08 to 1.05)	**3.02** (1.17 to 7.80)
Low Permafrost (< 2 %)	**31**	**0.30** (0.08 to 0.54)	**166** (22 to 435)	**0.31** (0.04 to 1.05)	**1.36** (0.31 to 7.80)
Fen-dominated Permafrost (17–62 %)	**5**	**0.24** (0.12 to 0.49)	**159** (58 to 250)	**0.33** (0.11 to 0.53)	**0.56** (0.37 to 0.78)
Bog-dominated Permafrost* (2–88 %)	**14**	**0.21** (0.08 to 0.43)	**405** (137 to 618)	**0.80** (0.25 to 1.20)	**2.44** (0.22 to 10.81)

n = No. lakes; Values in brackets indicate range of annual modelled values for lakes. *Thaw lakes of Gibson et al. (2015a).

yield from SM lakes was fairly high as well, and exceeded that in low-lying boreal plains and shield areas (WF,S). Fen-dominated plateau lakes with permafrost were found to have similar water yields (159 mm/yr) to fen-dominated non-permafrost lakes (166 mm/yr) situated mainly in lowlands, whereas bog-dominated plateau lakes with permafrost were found to have characteristically higher water yields on average (405 mm/yr) (Table 1). Gibson et al. (2019b) demonstrated good agreement between IMB and gauged estimates of water yield for the SAOS area, which is consistent with the SM lakes area in our analysis, although this region does not appear to be significantly affected by active permafrost thaw. Runoff ratios display similar patterns to water yield owing to low precipitation gradients across the region. Classification of bog-dominated permafrost lakes (deemed 'thaw lakes' by Gibson et al. (2015a)) was previously described and was based on their occurrence in areas with abundant bog collapse scaring, as well as anomalously high tritium content which was inferred to reflect recent thawing of modern permafrost (Gibson et al., 2016b).A similar finding of high tritium in thaw lakes has been recorded in other areas of northern Canada and elsewhere (e.g. Bond and Carr, 2018; Wan et al., 2019a, b). A most notable feature of the runoff ratio estimates is that bog-dominated thaw lakes had average runoff ratios of close to 80 %, with values as high as 120 % in some cases. In contrast, average runoff ratio is found to be 31 % for non-permafrost lakes and 33 % for fen-dominated plateaus. This is in close agreement with values for the runoff coefficient of 20–30% for boreal wetlands reported by Devito and Mendoza (2010). Here we ascertain, based on a 78 % longer observation period than Gibson et al. (2015a; 2016b), that there is a significant detectable enhancement of runoff due to permafrost meltwater contributions in bog-dominated watersheds in the RAMP network (Table 1). Temporal trends in water yields are shown by sub-group in Fig. 4b, and in particular, capture interannual fluctuations corresponding to wet and dry years. Box plots illustrate ranges of annual water yield and precipitation across each lake sub-region over time (Fig. 6). With one exception, precipitation is found to exceed water yield in non-permafrost sub-regions in all years (SM, WF, S) but water yield often exceeded precipitation in dry years within many permafrost-affected sub-regions (NE, BM, CM).

Water residence times were found to range from 0.22 to 10.81 years for individual lakes, the main determinant being the depth rather than the area of the lake. Residence time is also found to increase along a latitudinal gradient, with sub-region average values ranging from a low of 0.84 years in NE lakes to a high of 3.02 years in S lakes. Bog-dominated thaw lakes typically had longer residence times than non-permafrost lakes (1.36 versus 2.44 years, respectively). While residence time does not appear to be factor in determining thaw lake status, longer residence times would presumably serve to attenuate the isotopic signature of higher thaw-source throughputs than would shorter residence times. It is important to note that permafrost degradation has likely occurred over the past century in this region, possibly since the Little Ice Age (Zhang et al., 2006), significantly longer than the residence time of the lakes. Similarity of fen-dominated plateau lakes and non-permafrost lakes is noted, which may reflect that frozen ground in fens may be less influential on runoff processes than for bogs.

Mann-Kendall trend tests (Gibson et al., 2019d) reveal a combination of both positive MK tau values for E/I, WY and WY/P (97/150) and negative values (53/150), although only a few lakes have significant trends (4/150), all positive. Residence time was found to be mostly negative trending (33/50 lakes) although only SM7 and BM8 had significant negative trends.

4.5. Hydrological drivers and indicators

PCA was conducted to further explore relationships between the derived site-specific water balance outputs (evaporation/inflow, runoff ratio, water yield and residence time), and the underlying hydrologic drivers of the system, including location, climate parameters, lake/watershed characteristics, land cover characteristics and permafrost. Results are summarized in a PCA biplot (Fig. 7). As noted, variations along the PC1 axis accounted for 37.39 % of variability in the dataset and variations along PC2 accounted for 16.51 % of variability in the dataset. Combined, these factors explain 53.90 % of variability. Variations along the PC1 axis correspond mainly to the influence of land cover (bog versus fen), and permafrost, which occurs mainly in the plateau bogs. Note that one landscape sub-type, bog forest collapse scar (BFXC), which was shown by Gibson et al. (2015a) to be the most influential water yield driver, is indistinguishable from % Bog and % permafrost, reflecting nearly ubiquitous occurrence of collapse features in all regional plateau bogs. Weaker influences on PC1 include DBA and %OW. The most influential factors for PC2 are % Upland, Elevation, and LA. Plotting in the lower left quadrant (Fig. 7), climate drivers (P, E, T) and elevation are apparently influential for both axes and for isotopic composition of lake water and E/I. Plotting in the lower right quadrant, LA, V, DBA, %Bog, and % permafrost appear to be most influential for WY, WY/P, and τ. It is important to note that vectors for these water balance parameters are roughly perpendicular to the climatic drivers (P,E, and T), as they are with the isotopic composition of lakes, and E/I, and so are apparently providing unique information beyond the isotope-based metrics such as E/I used in some previous assessments (Turner et al., 2014; MacDonald et al., 2016; Narancic et al., 2017). Precipitation appears to be more influential with respect to hydrologic conditions in the southern sub-groups (SM,WF) than it is in the remaining groups, which is consistent with reduced influence of permafrost. WY and WY/P are also normal to Elevation, which does not support use of elevation alone to predict runoff (or runoff ratio) suggested by previous analyses (Western Resource Solutions, 2004).

Overall, the PCA also reveals distinct clustering of sub-region groups (Fig. 7) confirming similarity of drivers and water balance parameters among nearby lakes. Latitude is also an underlying driver of the regional climate gradients, but was removed from the PCA to confirm that sub-group similarity is based on site characteristics rather than simply due to locational differences, as we have shown.

As reported by Gibson et al. (2015a), very distinct clusters are noted for CM and S lakes, whereby CM lakes are distinguished by greater extent of bog cover and permafrost in their catchment areas, and shield lakes, which lack significant bog area, are predominantly influenced by higher %Uplands which ranges between 31 and 56 %. Note that S1 is somewhat of an outlier among the S sub-group, plotting among the CM cluster, but due to its much larger volume (V) rather than due to bog cover or permafrost. BM, NE

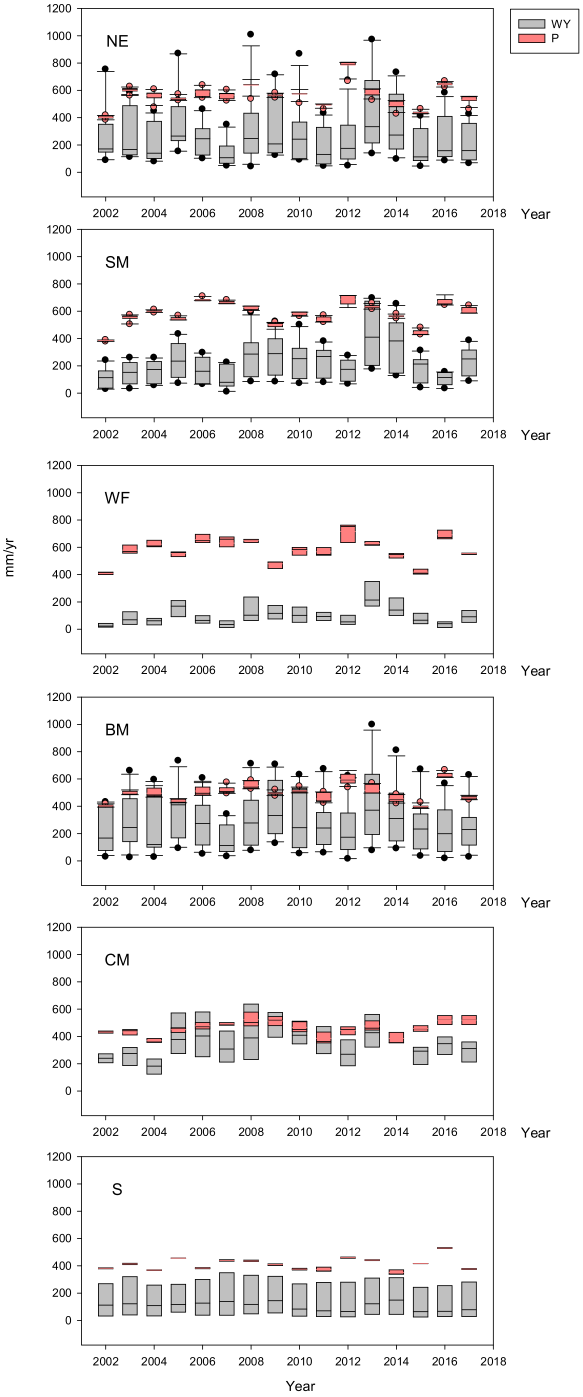

Fig. 6. Box plots showing water yield values computed for various lake sub-regions compared to annual precipitation amounts. The boundary of the box closest to zero indicates the 25th percentile, a line within the box marks the median, and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers (error bars) above and below the box indicate the 90th and 10th percentiles. Outliers are shown as solid circles.

and SM/WF are also significantly clustered. Importantly, bog plateau thaw lakes in BM and NE, as identified by star symbols, are shown to be shifted towards the upper right quadrant, revealing systematically larger LA, V, τ, WY, and WY/P for these lake-watershed systems.

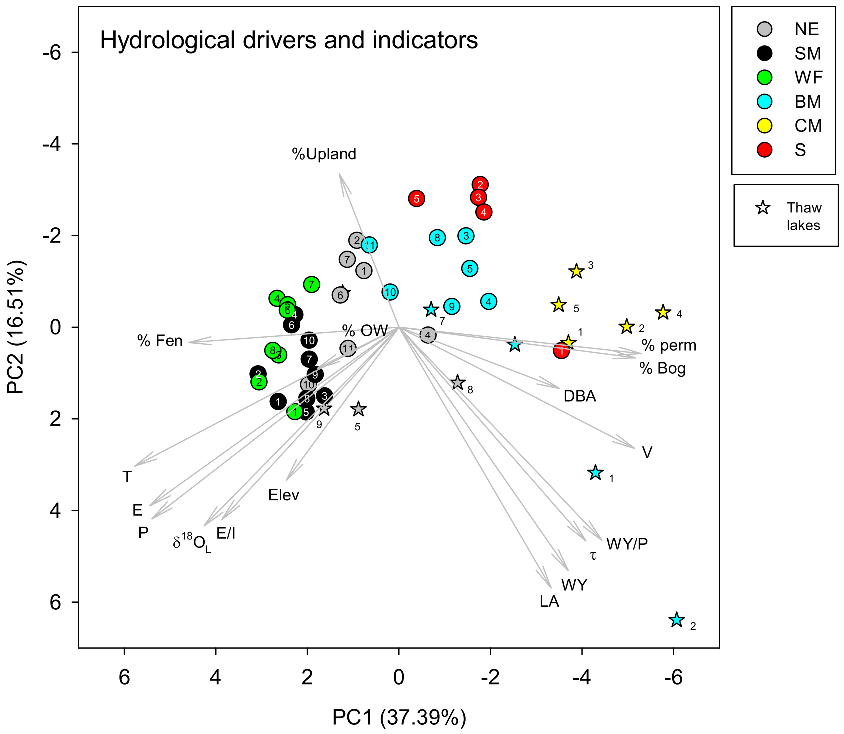

Fig. 7. PCA biplot showing lakes differentiated by sub-region and overlain by score plot for major variables tested in the analysis. Variations along PC1 correspond mainly to differences in % Bog, % Fen, and % permafrost, whereas variations along PC2 incorporate variations in many factors including % Upland, Elevation and LA. Note similarity for lakes within sub-groups (see text for discussion.

4.6. *Influence of thawing permafrost*

Correlation between permafrost, bog area and collapse scar area and WY or WY/P for the study watersheds was first noted by Gibson et al. (2015a) and is reaffirmed here based on a longer observational time series. Systematic links between thawing permafrost and runoff are clear, with direct evidence of permafrost collapse being an important constraint on this interpretation and the causal linkage of these processes (Gibson et al., 2015a). Another important observation that emerges after 16 years of monitoring is that water yield varies systematically although non-linearly with % permafrost (Fig. 8), whereby bog-dominated plateau watersheds with intermediate permafrost extent appear to have the highest calculated water yields as compared to those with both more extensive permafrost cover and less extensive permafrost cover. Given that permafrost extent is closely tied to permafrost degradation across the region, and presuming that bog-dominated plateau watersheds represent sites at different stages along a permafrost thaw trajectory, we postulate that water yield appears to increase in bog-dominated systems as permafrost degrades until roughly half the permafrost is thawed and then it reduces again as the watersheds completely thaw. Other drivers in addition to permafrost extent appear to be uninfluential in bog-dominated areas, however, less systematic %permafrost vs. water yield response at fen-dominated sites may reflect more complex runoff processes/controls at these locations. (Fig. 8).

Based on a similar isotopic perspective, comparable trajectories of water balance changes have been reported in other regions experiencing widespread permafrost thaw (see Wan et al., 2019a). We hereby propose a new conceptual framework for water balance characterization and prediction for lakes in thawing permafrost terrain. Conceptually, permafrost thaw can be considered an event hydrograph with a rising limb and falling limb controlled by the strength of the permafrost meltwater pulse (Fig. 9a). We anticipate that permafrost degradation will initially lead to increased runoff or water yield, as noted in Fig. 8 and in previous studies (Wan et al., 2019a, b). These additional contributions will eventually peak and then recede as permafrost degrades and eventually as it may no longer form. Permafrost degradation, as it proceeds, may lead to enhanced recharge below the pre-existing active layer, enhancement of subsurface hydraulic connectivity, formation and alteration of subsurface runoff pathways, development of taliks, strengthening of hydraulic exchange with features such as buried channels, capture of drainage from outside topographic divides that previously governed runoff, and/or formation of new open water bodies, collapse scars or internal lawns. Moreover, early thawing of extensive permafrost may be less effective at generating water yield due to contributions being limited to supra-permafrost meltwater, whereas formation of taliks and greater sub-permafrost interaction is expected to provide conduits for meltwater as thawing progresses. Eventually, thaw sources are expected to decline as ground ice storage slowly dwindles, the ground surface subsides, and collapse scars are formed. Although the shape and duration of the meltwater pulse will vary depending on initial permafrost conditions, climate change effects, and other site-specific controlling factors, we suggest that this basic framework can be applied to describe the stages of permafrost thaw response at individual sites, across various sub-regions, and/or at the regional scale.

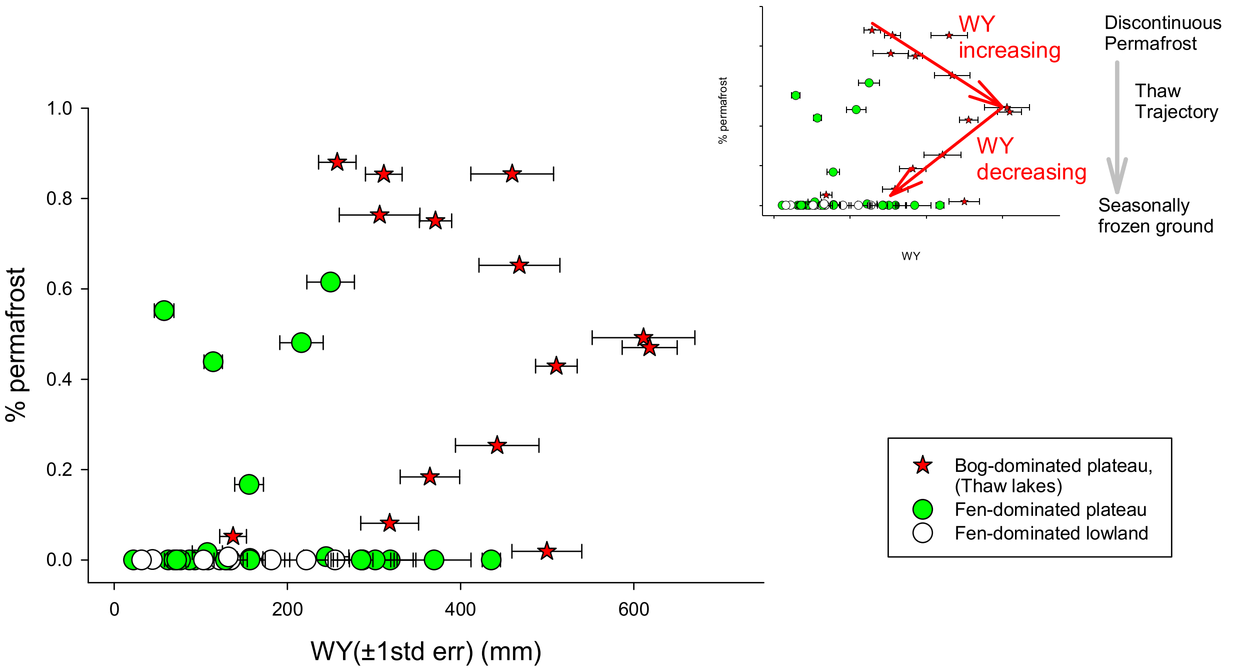

Fig. 8. Crossplot showing the relationship between water yield and % permafrost for lakes classified by three land cover groups. Inset (upper right) shows our thaw trajectory interpretation that water yield appears to increase in response to initial thawing and then peaks when permafrost extent is reduced to 40–60% permafrost, and then wanes again as ground ice is depleted.

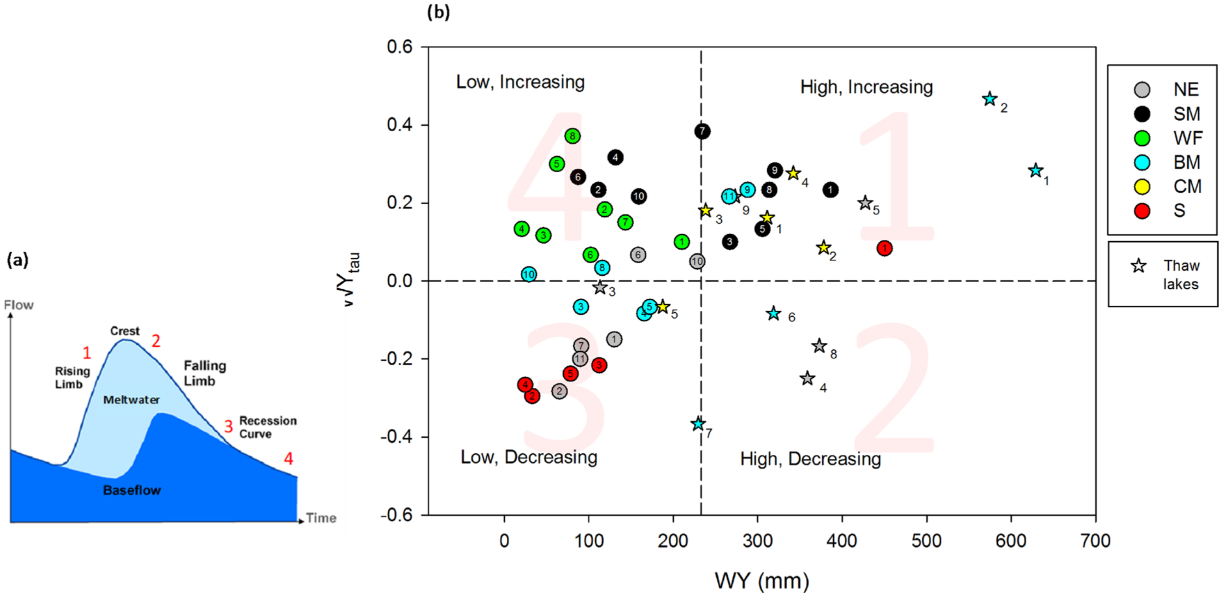

Fig. 9. (a) Conceptual permafrost meltwater hydrograph depicting rise and fall of runoff enhanced by ground thawing. Numbers 1–4 refer to stages of melt shown in (b) which depicts classification of site-specific water yield intensity and rate of change due to permafrost thaw. Note that lakes are colour coded by sub-region. Star symbols depict bog-dominated thaw lakes which are similarly colour coded by subregion.

The shape of the meltwater pulse for northern Alberta is undoubtedly influenced by prevalence of permafrost-bearing plateau bogs, including factors such as whether or not collapse features occur within or on the periphery of bogs, the later expectedly generating greater runoff. Runoff sources are likewise expected to transition both spatially and temporally from predominantly permafrost-meltwater sources to precipitation-dominated sources along such permafrost degradation trajectories/gradients (Wan et al., 2019a).

Using water yield and water yield trends (WY_{tau} vs. WY) from the 16-year lakes dataset, we illustrate classification of meltwater intensity and rate of change across the study region (Fig. 9b). We use average water yield based on our 16-year dataset, and calculate WYtau, which is a normalized index of the strength and direction of change in WY over the study period, similar to a Spearman Rank order tau value. Significance of trends is similarly evaluated with p-values. In this site-specific assessment, WY_{tau} is applied to identify increasing and decreasing trends in runoff, and average WY is used to separate high versus low WY systems. This allows for differentiation of sites into four categories that correspond to progressive stages along the meltwater hydrograph (Fig. 9a). Overall, it is evident that bog-dominated thaw lakes fall mainly within the upper right quadrant (category 1) signifying high, increasing WY. This accounts for 8 of 14 bog plateau thaw lakes and likely reflects conditions at these sites typical of the rising limb of the meltwater hydrograph. As such, it is expected that these watersheds will likely undergo increases in runoff, at least in the short term. Additional thaw lakes (4 of 14 thaw lakes) fall within the lower right quadrant (category 2), signifying high, decreasing WY. These sites appear to have already crested but still have high WY, and so conceptually, can be considered as being on the falling limb of the meltwater hydrograph. The remainder of bog-dominated thaw lakes (2 of 14 thaw lakes) fall within the bottom left quadrant (category 3) signifying low, decreasing WY. We postulate that these sites are on the recession limb of the meltwater hydrograph, and complete the meltwater hydrograph cycle. It is interesting to note that that the most northerly subgroup, the CM lakes, appear to be on the rising limb, whereas BM lakes situated in the heart of the region appear to straddle peak meltwater conditions, and NE lakes situated to the south are clearly on the falling limb or recession. We can also infer from field observations and based on previous studies of wetlands in the region that the southern parts of the study area, including the Stony Mountains (SM), and likely West of Fort McMurray (WF) have only localized occurrences of permafrost peatland, as well as more abundant peatland with internal lawns signifying permafrost degradation (e.g. Vitt et al., 1994, 1999; Beilman et al., 2000; Halsey et al., 2003). We interpret these areas to be predominantly post-thaw systems, responsive mainly to precipitation, and therefore can also be described in the hydrograph model as post-recession. Plotting in the upper left quadrant (Fig. 9), these lakes include many fen-dominated plateau lakes (category 4), and can mostly be classified as post-thaw systems with low WY, although as we note, 5 fen-dominated permafrost-bearing (5–9 %) watersheds are also included. These five systems appear to be producing some increased runoff but may be less productive than bog-dominated systems, although for unknown reasons. Due to lack of bog cover and minor permafrost influence we expect that increases in WY recorded for the majority of lakes falling in quadrant 4 is likely attributable to increased precipitation and/or storage changes.

As noted by Gibson et al. (2015a), thawing of permafrost in the more northerly subregions, NE, BM, and CM, is currently the main driver of hydrologic conditions in these areas as compared to more southerly subregions, SM and WF, where precipitation dominates. While it is not clear how long permafrost thaw will continue to augment discharge in these systems it is expected that future patterns in the post-thaw phase will likely mimic hydrology in the more southerly subregions. Based on the range of WY observed in this study, we estimate that permafrost thaw may account for up to 300 to 400 mm/year of additional runoff in the region, particularly on the bog-dominated plateaus. Considering that some watersheds in the CM, BM, and NE areas are still evidently subject to increases in WY, peak conditions in these areas may be somewhat higher. In general, potential runoff enhancement due to permafrost thaw is in broad agreement with enhancement in WY attributed to permafrost thaw in discontinuous permafrost terrain in the Yellow River headwaters of the Qinghai-Tibet plateau (Wan et al. 2019), which may account for up to 500 + mm of additional runoff to thaw lakes in extensive discontinuous permafrost versus seasonally frozen ground watersheds located nearby. Given the large number of isotopic surveys of thaw lakes that have now been conducted in North America, (e.g. MacDonald et al., 2016; Narancic et al., 2017; Wolfe et al., 2011; Turner et al., 2014), Siberia (Ala-aho et al., 2018) and Qinghai-Tibet (Cui et al., 2018; Yang et al., 2016; Gao et al., 2018), we suggest that these studies should be re-examined applying the WY metric in addition to enrichment or E/I metrics to gain a better understanding of the net impact of permafrost thaw across a range of cold regions settings. Importantly, application of this approach to time-series survey data will allow for clearer assessment of the stage and likely future trends in runoff related to permafrost thaw.

It is interesting to consider whether or not the permafrost thaw contribution estimates of up to 300–400 mm/year (4.8–6.4 m per 16 years) are realistic considering current knowledge of soil and permafrost characteristics, including thickness and distribution in the area. One important characteristic of permafrost in the region is a lack of massive ground ice, as noted by O'Neill et al. (2018). Peat soils have been shown typically to have a porosity ranging from 80–90% when frozen (Zoltai and Tarnocai, 1975). In a simple vertical system, generation of the estimated 4.8–6.4 m of runoff would require a minimum thawing of 5.3–8.0 m over the 16-year study period. Given that this level of augmentation to produce peak water yields is noted for watersheds with close to 50 % permafrost cover, we suggest that degradation in the zones with permafrost would need to be roughly twice that, or the equivalent of thawing of 10–16 m of frozen soil. While direct measurements of permafrost thickness are not available for comparison across the study region, the veracity of our estimate can be compared to at least one Canada-wide study that used a process-based model of Northern Ecosystem Soil Temperature (NEST) to simulate changes in permafrost conditions including depth to the permafrost table and depth to the permafrost base since the Little Ice Age (Zhang et al., 2006). In this analysis, the permafrost region was subdivided into permanent and ephemeral zones, the latter being the the unstable permafrost zone subject to active melting. For the ephemeral permafrost zone, which accounts for 11 % of Canada's land mass situated near the southern limits of discontinuous permafrost, and also includes our study area, Zhang et al. (2006) estimated that the permafrost base had been reduced on average by 17 m with a maximum reduction of 50 m in some areas. While these estimates are a first- approximation, they suggest that our own calculations and understanding of the permafrost thaw processes in the study region are plausible. It is important to note that peat deposits where permafrost has tended to form are mostly limited to less than 10 m thickness, although underlying drift thicknesses may range from 0 to 200 + m. While bogs are likely the main source of meltwater, the strength of the water yield response suggests that alteration of the fundamental subsurface hydrology and flowpaths may be occurring.

Due to the observed pH increase occurring in many lakes within the study network (Gibson et al., 2019d), it is also imperative that the role of permafrost thaw on runoff water chemistry be considered, as well as the timing, peak and eventual decline in such contributions. Permafrost degradation in bogs is expected to lead to collapse and release of dissolved solids including inorganic carbon and may lead to significant enhancements in surface/groundwater interactions as ombrotrophic bogs potentially will collapse and transition to minerotrophic fens. One important finding in this study is the clear identification of unique hydrologic responses in bog- and fen-dominated watersheds, and secondarily differences noted between response of lakes in fen-dominated plateaus and fen-dominated lowlands. Mechanistic differences in pH and geochemistry of these watershed types are expected to be important in developing a better understanding of the significance and trajectory of climate change and development impacts across the region.

5. Conclusions and implications

Hydrology of 50 wetland-dominated watersheds in northeastern Alberta is found to be driven by a combination of factors including land cover, watershed morphometry, and climate. Changes in the boreal hydrologic system are attributed mainly to permafrost thaw, which can account for several hundred millimetres of sustained runoff to lakes and presumably to rivers, for decades or longer. One important determinant of hydrologic changes in the watersheds is presence of bogs and fens, the bog/fen ratio, and % permafrost.

While relatively short-term studies have characterized hydrology of wetland-dominated watersheds in Alberta (Prepas et al., 2001; Gibson et al., 2002), this study builds upon a 9-year IMB assessment by Gibson et al. (2015a) to provide a valuable 16-year IMB assessment of hydrologic indicators for 50 lakes and their respective watersheds, that represents an improved long-term quantitative characterization of important hydrological processes in a largely ungauged region.

Significantly, this study demonstrates a refined approach for assessing permafrost thaw status, allowing for sites to be classified as being on the rising limb, peak, falling limb or recession limb of the permafrost meltwater runoff pulse. It is anticipated that this framework may be used to better understand, quantify, and map permafrost impacts from regional surveys in active permafrost degradation zones. Importantly, the existence of a permafrost thaw cycle helps to explain why hydrologic impacts due to monotonic regional changes in climate drivers, especially temperature, precipitation, and/or evaporation may not result in monotonic changes to water balance of lakes or their watersheds.

As noted by Gibson et al. (2015a), understanding of the permafrost degradation process in the region would benefit from additional monitoring and field work to directly characterize the processes operating in areas with degrading permafrost and to better understand the likely impacts of eventual decline in meltwater sources. Possible impacts may include lower water levels, reduced runoff, pH and chemical changes, and potentially might lead to lake acidification as water yield associated with permafrost thaw declines.

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