LETTER

Multi-year isoscapes of lake water balances across a dynamic northern freshwater delta

Casey R Remmer 1, Laura K Neary 1, Mitchell L Kay 1, Brent B Wolfe 2 and Roland I Hall 1

1 Department of Biology, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada
2 Department of Geography and Environmental Studies, Wilfrid Laurier University, Waterloo, Ontario N2L 3C5, Canada

E-mail: bwolfe@wlu.ca

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Abstract
Sustainable approaches capable of tracking status, trends and drivers of lake water balances in complex, remote landscapes are needed to inform ecosystem stewardship and water-security actions. At the Peace-Athabasca Delta (Alberta, Canada), a globally recognized freshwater floodplain landscape, concerns about water-level drawdown and multiple potential stressors have prompted need to improve knowledge of lake water balances and establish a lake monitoring program. Yet, the delta’s remoteness and dynamic nature present challenges to these goals. Here we use over 1000 measurements of water isotope composition at ∼60 lakes and 9 river sites during the spring, summer and fall of five consecutive years (2015–2019) to elucidate patterns in lake water balance over time and space, the influential roles of evaporation and river floodwaters, and relations with meteorological conditions and river water levels. Calculation of evaporation-to-inflow ratios using a coupled-isotope tracer approach, displayed via generalized additive models and geospatial ‘isoscapes’, reveal strongly varying lake water balances. Results identify distinct areas vulnerable to lake-level drawdown, given the likelihood of continued decline in ice-jam flood frequency, longer ice-free season duration and reduced snowmelt runoff. Results also demarcate areas of the delta where lakes are more resilient to factors that cause drawdown. The former defines the Peace sector, which is influenced by floodwaters from the Peace River during episodic ice-jam flood events, whereas the latter describes portions of the active floodplain environment of the Athabasca sector which receives more frequent contributions of Athabasca River floodwaters during both spring ice-jam and open-water seasons. Efficiency of water isotope tracers to capture the marked temporal and spatial heterogeneity in lake water balances during this 5 year time span, and their diagnostic responses to key hydrological processes, serves as a foundation for ongoing lake monitoring, an approach readily transferable to other remote and dynamic lake-rich landscapes.

1. Introduction

Security of water supply is essential to sustain vitality of ecosystems, abundance of traditional food sources and responsible development of natural resources. Yet, inland freshwater ecosystems are amongst the most threatened, due to their vulnerability to climate change and human development (e.g. Hassan et al. 2005, Dudgeon et al. 2006, Woodward et al. 2010). In northwestern North America, rapid warming continues to alter seasonal distribution of snow and rain, shorten duration of seasonal ice-cover, and increase rates of evaporation and permafrost thaw (Schindler and Smol 2006). Shrinking snowpack and glacier volumes at mountainous headwater regions have reduced river flows at a time when population growth and industrial development have increased demand for water (Schindler and Donahue 2006,
Wolfe et al. (2008a, Sauchyn et al. 2015). Altered river flows and sediment regimes are affecting the structure, function and water quality of rivers and floodplains, including key waterways used for hydropower, natural resource extraction, water supply, and transportation (Prowse et al., Schindler and Donahue 2006). Drying up of lakes, conversion of wetlands to shrublands, reduced navigability of water routes, and deterioration of wildlife habitat are among the many changes that natural resource agencies and stakeholders are increasingly challenged to mitigate and adapt to (Schindler and Smol 2006, Carroll et al., Chavez-Ramirez and Wehtje 2011, Smith et al., Huot et al. 2019).

Despite the above outcomes, it remains challenging to identify the relative importance of multiple potential anthropogenic stressors and processes on freshwater resources, because they typically operate over broad spatial and temporal scales that are inadequately captured by existing monitoring records (Wilkinson et al. 2020). Yet, accurate identification of the cause(s) of change is required to develop effective policies and actions aimed at protecting water-rich northern landscapes. Thus, government agencies, Indigenous communities, and multi-stakeholder boards urgently require innovative collection and analysis of environmental data, integrated over a broad range of spatial and temporal scales, to inform decisions aimed at ensuring water-rich landscapes remain abundant, clean and productive for future generations.

These stewardship challenges converge at the Peace-Athabasca Delta (PAD) in northern Alberta, Canada, where declining lake levels have been a focal concern for decades (e.g. PADPG 1973, Mikisew Cree First Nation (MCFN) 2014). A large body of literature on potential causes has variably attributed lake-level drawdown to climate change, upstream regulation of Peace River flows since construction of the WAC Bennett Dam in 1968, consumptive water use by upstream oil sands development on the Athabasca River, and natural deltaic processes (e.g. Prowse and Conly 2002, Schindler and Donahue 2006, Wolfe et al. 2012, 2020, Beltaos 2014, 2018, Kay et al. 2019). Regardless of cause, reduction in freshwater abundance has had consequences for wildlife (Straka et al., Ward and Gorelick 2018, Ward et al. 2020) and access to traditional territory (Mikisew Cree First Nation (MCFN) 2014, Vannini and Vannini 2019). The PAD is a large (6000 km²), remote, lake-rich floodplain landscape recognized as a Ramsar Wetland of International Importance and contributed to the listing of Wood Buffalo National Park (WBNP) as a UNESCO World Heritage Site. Given the critical role of water in this landscape, improved characterization of hydrological processes and their influence on lakes is essential to inform ecosystem stewardship decisions. However, the complexity of the PAD and its numerous lakes, whose water balances are varyingly controlled by river floodwater, snowmelt, rainfall and evaporation over a range of temporal and spatial scales (Prowse and Conly 2002, Wolfe et al. 2007), presents significant challenges to design effective hydrological monitoring approaches.

Prior water isotope tracer studies in the PAD have demonstrated their value for capturing snapshots of water balance for a season or year (Wolfe et al. 2007, 2008b, Wiklund et al. 2012, Remmer et al. 2018) and quantifying the extent and magnitude of ice-jam floods (Remmer et al. 2020), but the range and variability of contemporary lake hydrological conditions during recent time and over the ∼6000 km² expanse of the delta has not been adequately characterized. Here we use meteorological data, river water level records and water isotope compositions measured at ∼60 lakes and 9 river sites during spring, summer and fall of a 5 year period (2015–2019) to assess the influence of hydrological processes on landscape-scale spatial variation of lake water balances over seasonal to multi-annual time scales. This is required to evaluate their sensitivity and applicability as a lake hydrological monitoring approach for the delta and to serve as a foundation for water quality and contaminant assessment (Wolfe et al. 2012). The need for these environmental assessment tools was identified by federal and international agencies, which have recommended the development and implementation of an aquatic ecosystem monitoring program for the PAD capable of tracking changes in water supply, water levels and water quality, and the processes driving changes (WHC/IUCN 2017, Wood Buffalo National Park (WBNP) 2019). Integration of an isotope-mass balance model and geospatial analysis allowed development of isoscapes (sensu Bowen and Revenaugh 2003) for effective visualization of areas where lakes are most influenced by evaporative water loss and replenishment by river floodwaters and, respectively, identification of portions of the delta vulnerable and resilient to factors driving lake-level drawdown.

2. Methods

2.1. Study area

Lakes of the PAD are situated mainly within two distinct sectors, which differ in the relative roles of hydrological processes that influence lake water balances (figure 1; Wolfe et al. 2007). The northern Peace sector is a relic delta where lake water balance is strongly influenced by precipitation and evaporation, except during infrequent, widespread flooding caused by ice-jam events on the Peace River. The southern Athabasca sector, fed continuously by the Athabasca River, contains more active deltaic environments. Here, lake water balance spans a broader gradient of influence from river floodwaters during
both spring ice-jam and summer open-water seasons, while lake water balance in slightly more elevated areas is dominated by precipitation and evaporation. Three large lakes (Claire, Mamawi, Richardson) occupy central and southern locations of the PAD and receive continuous river through-flow. Low hydraulic conductivity of flood-deposited fine-grained sediment that line basins, low horizontal gradients between lakes and discontinuous permafrost result in negligible influence of groundwater on lake water balances in the PAD (Nielsen 1972, Prowse et al 1996, Wolfe et al 2007). The ice-free season typically begins in May and extends until at least late September, whereas lakes are ice covered from October through April.

2.2. Water isotope composition and designation of flood status
Surface water samples were collected from 57–60 lakes and 9 river sites spanning the two main sectors of the PAD three times per year during the ice-free seasons of five consecutive years, 2015–2019 (figure 1; supplementary information 1 (available online at https://stacks.iop.org/ERL/15/104066/mmedia)). To capture and compare the effects of hydrological processes (i.e. snowmelt, rainfall, spring ice-jam flooding, open-water flooding and evaporation), samples were consistently collected during two to three-week intervals in the spring (May), summer (July) and fall (September) of each year. An exception occurred in 2016 when the Fort McMurray regional wildfire...
delayed our spring sample collection by three weeks (June). Well-mixed water samples were collected mid-lake (or mid-channel) from a depth of ∼10 cm and stored in sealed 30 ml high-density polyethylene bottles. Lake and river water isotope compositions were measured by off-axis integrated cavity output spectroscopy at the University of Waterloo—Environmental Isotope Laboratory (UW-EIL). Isotope compositions are expressed as δ-values, representing deviations in per mil (‰) from Vienna
Figure 3. Water isotope compositions for 57–60 lake (circles) and 9 river (triangles) sites during the spring, summer and fall of 2015–2019 displayed on $\delta^{18}O$–$\delta^2H$ graphs. Solid blue circles are lakes that received river floodwaters while grey circles are lakes that did not receive river floodwaters prior to sampling. Open triangle is the Claire River (R9), which serves to identify flooding along the Peace River and its distributary channels. LMWL refers to the Local Meteoric Water Line ($\delta^2H = 6.7 \delta^{18}O - 19.2$; Wolfe et al. 2007) and the LEL is the predicted LEL ($\delta^2H = 4.3 \delta^{18}O - 63.5$) constrained by the mean annual isotope composition of precipitation ($\delta_P$), the terminal basin steady-state isotope composition ($\delta_{SSL}$) and the limiting non-steady-state isotope composition of a water body approaching complete desiccation ($\delta^*; \text{see supplementary information 2}$).

Standard Mean Ocean Water (VSMOW) such that $\delta$-sample = $\left[ \frac{R_{\text{sample}}}{R_{\text{VSMOW}}} - 1 \right] \times 10^3$, where $R$ is the $^{18}O/^{16}O$ or $^2H/^{1}H$ ratio in the sample and VSMOW. Results of $\delta^{18}O$ and $\delta^2H$ analyses are normalized to $-55.5\%o$ and $-428\%o$, respectively, for Standard Light Antarctic Precipitation (Coplen 1996). Analytical uncertainties are $\pm 0.2\%o$ for $\delta^{18}O$ and $\pm 0.8\%o$ for $\delta^2H$. In-situ measurements of specific conductivity were obtained using a YSI ProDSS sonde.

Lakes that received river floodwaters during the spring (assumed to result from ice-jams, as in 2018; Remmer et al. 2020) and open-water season were identified using mainly lake and river water isotope compositions, supported by measurements of specific conductivity and field observations. Following Remmer et al. (2020), lakes were designated as flooded if (1) lake water isotope values were close to or overlapping with water isotope compositions of flowing rivers, (2) lake specific conductivity values were close to the range of the river water values, and/or (3) there was visible evidence of flooding, such as water colour and turbidity (assessed in situ) similar to the closest river or channel, and flooded lake margins and debris (i.e. logs) that appeared to have been carried in by the recent floodwaters (supplementary information 1, tables S1.2–5).

2.3. Water balance derivation and analysis

Evaporation-to-inflow (E/I) ratios, an informative water-balance metric, were calculated from lake water isotope compositions using a coupled-isotope tracer...
Figure 4. (a) Generalized additive models (GAMs) capturing seasonal trends (as lines) in the evaporation-to-inflow (E/I) ratios of lakes (circles) in the Peace (yellow) and Athabasca (blue) sectors of the Peace-Athabasca Delta. Shaded areas represent the 95% confidence interval of the trendline. The data are binned by month of sample collection. (b) 'Isoscapes' displaying spatial interpolation of lake evaporation-to-inflow (E/I) ratios across the Peace-Athabasca Delta during spring, summer and fall of the five-year period 2015–2019. Black dashed lines represent flood extent while white dashed lines represent areas with E/I > 1.0 (i.e. net evaporative drawdown). Warmer colours represent higher E/I ratios and colder colours represent lower E/I ratios, ranging from zero to 1.5, as indicated in the scale. Data are contoured at 0.1 intervals encompassing reasonable levels of uncertainty in model output. Individual lake sites are indicated as black circles.
method (Yi et al 2008) and an isotope framework representing average meteorological conditions during 2015–2019 (supplementary information 2). This approach to isotope mass-balance modelling systematically accounts for varying input water isotope compositions in the calculation of E/I ratios, which are evident in the scatter of lake water isotope compositions about the predicted Local Evaporation Line (LEL; see figure 3 below). Consistent with other studies (MacDonald et al 2017, Remmer et al 2018), we set E/I ratios to 1.5 for lakes experiencing strong non-steady-state conditions. Temporal trends of E/I ratios were visualized as generalized additive models (GAMs) for each sector and year using RStudio v1.2.5001 (R Core Team 2019), and the ggplot2 v3.2.1 (Wickham 2016) and mgcv v1.8.28 (Wood 2017) packages. Spatial interpolations of E/I ratios were presented as ‘isoscapes’ for all 15 sampling campaigns by ordinary kriging using ArcMap 10.7.1 software because Moran’s I was significant (p < 0.05; supplementary information 3). The extent of river floodwaters across the landscape and areas of lakes with E/I > 1.0 (signifying net evaporative drawdown) were delineated on the isoscapes by inverse-distance weighting using ArcMap 10.7.1 software.

3. Results

3.1. Meteorological conditions and river water levels

Monthly mean air temperature varied seasonally, but did not differ substantially among years or from the 1981–2010 climate normal, except 2016 which was cooler in the spring and warmer in summer through fall (figure 2(a)). Seasonal and annual precipitation, however, did vary notably among years and relative to the climate normal. Snowfall (precipitation during November to March) was below normal during all five years. Rainfall (precipitation during May to September) was below normal in the spring (April, May) and early to mid-summer (June, July) of each year, except for July 2015 and June 2018. Late summer and early fall (August, September) rainfall was below normal in 2015 and 2018, and above normal in 2016 and 2019. An unusually large rainfall event occurred on August 16, 2019, which contributed 44.3 mm of the total monthly precipitation (106.5 mm).

Peace and Athabasca river water levels varied seasonally and between years (figure 2(b)). For both rivers, water levels were typically higher during the spring melt and lower in summer and fall, but there are exceptions. For example, Athabasca River water levels in summer 2019 exceeded those of spring. Marked increases of water level of the Peace River occurred in June and September 2016, August 2018 and July 2019. For the Athabasca River, substantial peak water levels occurred in late April and early May 2018. Summers of 2018 and 2019 were characterized by markedly higher water levels on the Athabasca River than the other years. In contrast, low water levels and low variability for the Athabasca River occurred in 2015 and spring of 2019.

3.2. Lake and river water isotope compositions

River water isotope compositions fall close to the Local Meteoric Water Line (LMWL) as the rivers convey considerable glacier- and snow-melt which undergo minimal subsequent evaporation (figure 3). In contrast, lake water isotope compositions span the spectrum of the LEL, reflecting a gradient of isotopically-depleted lakes strongly influenced by river floodwaters to isotopically-enriched lakes strongly influenced by evaporation. Varying numbers of lakes that received river floodwaters during spring ice-jam flooding were identified in 2017, 2018 and 2019 (figure 3). The largest spring ice-jam flood event was in May 2018 (27 lakes flooded), with smaller extent of flooding occurring in 2017 (11 lakes) and 2019 (9 lakes). Open-water flooding occurred during summers of 2017–2019 (5, 7 and 13 lakes flooded, respectively), and in fall of 2018 (8 lakes) and 2019 (14 lakes).

We note that the Claire River (R9; figure 3) plots along the LEL and separate from the other rivers during most sampling periods. This site is a relic river channel in the Peace sector that has become disconnected from the Peace River and undergoes evaporative enrichment similar to a disconnected lake. Exception to this was in the spring and fall of 2018 when this site is isotopically depleted and plots close to the flowing river sites as a result of re-connection with the Peace River during high water events. Thus, the Claire River acts as a useful indicator for flooding along the Peace River and its distributary channels.

3.3. Trends in lake E/I ratios

E/I ratios for the lakes vary substantially across the sampling periods and sectors, ranging from near 0 to greater than 1.0 (i.e. net evaporative drawdown; figure 4(a)). GAM-defined trendlines in E/I ratios display patterns reflecting broad similarities and differences in hydrological processes influencing lake water balance in the Peace and Athabasca sectors of the delta. During each year, trendlines indicate higher E/I ratios (i.e. more intense evaporation) in lakes of the Peace sector than the Athabasca sector, consistent with the relic deltaic environment of the former. For three of the five years (2015, 2016, 2019), Peace and Athabasca E/I trendlines are similar, but offset, rising from spring to summer and then declining in the fall. The increase in E/I ratios from spring to summer is generally steeper in the Peace sector than the Athabasca sector and can be attributed to strong influence of evaporation and absence of open-water flooding in the Peace sector. We note that the E/I trendline exceeds 1.0 in the Peace sector during all
years signifying net evaporative water loss (except 2018), whereas the E/I trendline remains well below 1.0 for lakes in the Athabasca sector. Parallel declines in the trendline from the summer to fall during 2016 and 2019 in both sectors are due to rainfall, with additional contributions from open-water flooding in the Athabasca sector in 2019 (also see below and figure 4(b)).

Distinct differences in seasonal E/I trendlines for lakes in the Peace and Athabasca sectors occur during 2017 and 2018. In 2017, the E/I trendline rises rapidly in the Peace sector during the open-water season to values >1.0 and remains high in the fall. In the Athabasca sector, the trendline rises less rapidly between spring and summer and continues to rise steadily in the fall. In 2018, E/I trendlines are also not parallel. E/I ratios rise in lakes of the Peace sector for the entire open-water season, whereas the E/I trendline for the Athabasca sector lakes shows a small initial rise and then a decline from summer to fall. Differences in the spring-to-summer E/I trendlines during these two years are due to spring ice-jam flooding in the Athabasca sector, which was extensive in 2018 (Remmer et al. 2020). High E/I ratios in the Athabasca sector during summer and fall of 2017 reflect the evaporative response of lakes during a year without open-water flooding (also see below and figure 4(b)). This is in contrast to 2018 and 2019, when E/I ratios decline in lakes of the Athabasca sector during the fall due to open-water flooding (also see below and figure 4(b)).

3.4. Isoscapes of lake E/I ratios

Additional insight into spatial variation and influence of key hydrological processes on lake water balance, including evaporation and river flooding, can be gleaned from E/I isoscapes for the 15 sampling periods (figure 4(b)). Regions where E/I ratios exceed 1.0 are noteworthy as they indicate lake-level drawdown by net evaporation. These regions tend to include the central and northwestern Peace sector and the southwestern Athabasca sector (summer and fall 2015, 2017, 2019, spring and summer 2016). Although the meteorological data captured in Fort Chipewyan do not indicate particularly low rainfall in 2016, high E/I ratios in the northwestern portion of the Peace sector are consistent with locally arid conditions that promoted wildfires in this area in June through July. Massive wildfires also occurred at the upstream town of Fort McMurray during this period, indicating dry conditions persisted in the region. During the subsequent summer and fall of 2017, high E/I ratios across much of the Peace sector and the southwestern Athabasca sector align with field observations of lake desiccation (also see Remmer et al. 2020).

Also delineated on figure 4(b) is river floodwater extent, an important source of water to lakes which offsets water loss by evaporation and produces low E/I ratios. We identified influence of river floodwaters on lakes during 8 of 15 sampling campaigns (53%) including ice-jam flooding during springs of 2017–2019, and open-water flooding during summers of 2017–2019, which remained detectable during falls of the latter two years. Ice-jam flooding in 2017 and 2019 was limited to lakes in the central Athabasca sector and along the Athabasca River. In contrast, ice-jam flooding in 2018 was widespread and encompassed most of the Athabasca sector and a few lakes in the north-central Peace sector (Remmer et al. 2020). Open-water flooding also varied in extent, but was generally restricted to the central Athabasca sector and some lakes farther east near the Athabasca River’s terminus. Also, continuous river through-flow at Mamawi Lake is identified as persistent low E/I in a localized central region of the PAD.

4. Discussion

Analysis of >1000 samples for water isotope composition collected during 15 sampling campaigns over 5 years (2015–2019) in the PAD provides exceptional insight into hydrological processes influencing lake water balances across this dynamic, remote floodplain landscape. Quantification of E/I ratios, summarized using GAMs and depicted as isoscapes, provide an effective approach to delineate patterns of lake water balance over time and space and their underlying causes. Our study captured two years with no river flooding (2015, 2016), three years with river flooding (2017–2019), and marked responses of lake water balance to absence and occurrence of this key hydrological process. The data reveal distinctive hydrological differences between Peace and Athabasca sectors of the delta and that substantial seasonal and multi-annual oscillation in lake water balance are an inherent feature of this complex northern freshwater landscape, scales of variability necessary to document and appreciate as a basis for informed conservation and management (Wilkinson et al. 2020).

A key outcome is identification of spatial and temporal ‘hotspots’ of lake drying. Results show that evaporative water loss is greatest during summer and persists in the north-central and northwestern Peace and southwestern Athabasca portions of the PAD (figures 4(a), (b)), consistent with recent observations and concerns of aquatic habitat deterioration (Mikisew Cree First Nation (MCFN) 2014, Independent Environment Consultants (IEC) 2018). Marked evaporative water loss during portions of 2015–2017 correspond to years of low water level on the Athabasca River (figures 2(b), 4(b)). Occasional high-water peaks on the Peace River during the open-water season had little effect on the lake water balances across the Peace sector, as expected (Prowse and Lalonde 1996). This highlights the vulnerability of lakes in the relic Peace sector and an elevated portion of the Athabasca sector to drawdown and desiccation,
especially with anticipated further declines in the frequency of ice-jam flooding, longer ice-free seasons leading to increased evaporation, and reduced snowmelt runoff (Schindler and Smol 2006, Wolfe et al. 2008a). Indeed, all five years of our study were characterized by below normal snowfall, perhaps signifying a shift to reduction in supply of this source of water to lakes in the PAD, although influence of rainfall lowered E/I ratios during the fall of some years (2016, 2019). These findings align with a long-term trend of increasing evaporative influence on lakes in the Peace sector evident in sediment records (Wolfe et al. 2008a, 2020, Remmer et al. 2018) and identify regions of the delta where water security is most threatened.

A main source of lake water replenishment is river floodwaters, as revealed by low E/I ratios in lakes within flooded areas delineated in the isoscapes (figure 4(b)). The approach used in this study identified a major ice-jam flood event (spring 2018), as well as more localized spring ice-jam flooding (2017, 2019) and open-water flooding (2017–2019). Both ice-jam and open-water flooding occurred almost exclusively in the Athabasca sector and preferentially along the Athabasca-Embarass-Mamawi river corridor owing to the Embarras Breakthrough (figure 1), a natural river avulsion that occurred in 1982 and has had profound influence on hydrological trajectories of lakes across the Athabasca sector (Kay et al. 2019). Evidence of flooding in the Athabasca sector during intervals of 2017–2019 correspond to high water recorded on the Athabasca River (figures 2(b), 4(b)). Documentation of frequent river floodwater inundation reveals that lakes along preferential flow pathways in the Athabasca sector are most resilient to factors that cause drawdown, substantiating earlier claims (Wolfe et al. 2008b, Kay et al. 2019). While spring ice-jam flooding is long known to be an important hydrological process for replenishing slightly more elevated (perched) lakes (Prowse and Lalonde 1996), open-water flooding in the Athabasca sector evidently is also a major contributor to maintaining lake water balances in this part of the PAD, despite not being widely recognized (Independent Environment Consultants (IEC) 2018). Results further demonstrate that the two sectors of the delta largely function as distinctly different landscapes. The Peace River lies at lower elevation than the delta, thus it bypasses the Peace sector except during episodic ice-jam flood events. In contrast, the Athabasca River lies at higher elevation than substantial areas of the PAD. Thus, the Athabasca River flows continuously into and through the Athabasca sector, branching into several distributaries which supply water to low-lying lakes during both the spring (ice-jam) and open-water seasons.

A novel outcome of our 5 year study is that the water balances of lakes in the PAD are markedly dynamic over time and space, as visualized by the isoscapes (figure 4(b)). Influence of river floodwaters on lake water balances was detected in more than half (8 of 15) of our sampling campaigns, demonstrating the value of systematic water isotope sampling and analysis to capture the effects of this important hydrological process which may otherwise occur undocumented. Further demarcation of (1) portions of the Peace and Athabasca sectors most vulnerable to lake-level drawdown and (2) portions of the Athabasca sector most resilient to lake-level drawdown requires that effective hydrological monitoring programs and stewardship practices need to consider and incorporate these distinct features of the landscape (see also Wolfe et al. 2012). Water isotope tracers provide a sensitive and efficient approach to address this need. Although regional and national lake water balance syntheses are increasingly using water isotope tracers (e.g. Brooks et al. 2014, Gibson et al. 2017, MacDonald et al. 2017), we advocate that sustained and long-term sampling and analysis is required for highly dynamic freshwater landscapes such as deltas and floodplains to capture the range and variability of contemporary hydrological conditions and to detect potentially shifting relative influence of important drivers.

Use of water isotope tracers provides a snapshot of lake water balance which integrates processes that occurred in the days to weeks preceding sample collection, but may not accurately capture hydrological processes occurring at shorter or longer frequencies. Thus, opportunities exist to incorporate other methods and approaches to complement water isotope tracers. For example, water-level loggers quantify lake-level rises and declines at short time-steps (e.g. hourly to daily), and detected the influence of the large rainfall event in August 2019 that was not well captured by the water isotope data based on samples collected a month later (Neary et al. 2019). Remote sensing has also been used to identify changes in surface water area in the PAD (Töyrä and Pietroniro 2005, Montgomery et al. 2019). Although water-level loggers and remote sensing inform about timing and magnitude of change in lake depth and area, combined use of water isotope tracers can identify the causative processes. Additional meteorological stations across the 6000 km² area of the PAD would likely reveal more localized weather patterns and improve the interpretation of water isotope data. Increased lake sampling density could improve spatial interpolation in sparsely sampled areas, such as the central portion of the delta. Nonetheless, the sample density resulted in consistent statistically significant spatial autocorrelation which allowed for interpolation of E/I ratios, and revealed patterns that align with available records of hydrological processes. This suggests our approach provides knowledge at spatial and temporal scales relevant to conservation.
goals, and can serve for systematic and sustained long-term monitoring as needed to detect and document aquatic ecosystem change (Xenopoulos 2019).

5. Conclusions

Five consecutive years of systematic seasonal sampling of water isotope composition from ~60 lakes and 9 river sites across the remote, expansive Peace-Athabasca Delta identify the key roles of evaporation and river flooding on the water balance of its abundant, shallow lakes. An important feature is the marked seasonal to multi-annual and spatial variability of lake water balance and the hydrological processes driving the variation. Temporal and spatial patterns of isotope-based E/I ratios emerged and provide a basis to forecast change in this dynamic freshwater landscape, given that evaporation and floodwaters directly influence vulnerability and resilience of lakes to drawdown. We identify hotspots of strong evaporative influence in the north-central and northwestern Peace and southwestern Athabasca portions of the PAD. These are regions most likely to exhibit water insecurity due to expected further declines in the frequency of ice-jam flooding, longer ice-free seasons leading to increased evaporation, and reduced snowmelt runoff. We also discern the influence of river floodwaters during 8 of 15 sampling periods, and identify the flood-prone central Athabasca sector as an area of low E/I ratios where lakes are less vulnerable to evaporative water loss. We envision that our five-year isotope-based hydrological study provides the foundation of a comprehensive aquatic ecosystem monitoring program for lakes of the PAD, offers a pivotal and timely contribution to execution of the Canadian federal government’s Action Plan for WBNP, and demonstrates the value of the approach for other dynamic, difficult-to-access lake-rich and floodplain landscapes.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

ORCID iDs

Casey R Remmer
https://orcid.org/0000-0003-2626-3012
Laura K Neary
https://orcid.org/0000-0002-8696-952X
Mitchell L Kay
https://orcid.org/0000-0001-6975-6242
Brent B Wolfe
https://orcid.org/0000-0003-4093-453X
Roland I Hall
https://orcid.org/0000-0002-0314-6449

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