Inconsequential effects of flooding in 2014 on lakes in the Peace-Athabasca Delta (Canada) due to long-term drying

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Abstract

Climate-driven decline in freshwater supplied by rivers draining the hydrographic apex of western North America has ramifications for downstream ecosystems and society. For the Peace-Athabasca Delta (PAD), floods from the Peace and Athabasca rivers are critical for sustaining abundant shallow water habitat, but their frequency has been in decline for decades over much of its area. Here, we assess current hydrological and limnological status in the PAD by integrating spatial and temporal data. Analysis of water isotope compositions and water chemistry measured at numerous lakes across the delta shows that hydro-limnological effects of the large-scale ice-jam flood event of 2014 failed to persist beyond the early ice-free season of 2015. Isotope-inferred paleohydrological records from five hydrologically representative lakes in the PAD indicate that periodic desiccation during the Little Ice Age occurred at the most elevated basin in response to locally arid climatic conditions, yet other lower elevation sites were influenced by high water level on Lake Athabasca owing to increased snowmelt- and glacier-derived river discharge. In contrast, water isotope data during the past 15 yr at all five lakes consistently document the strong role of evaporation, a trend which began in the early to mid-20th century according to sediment records and is indicative of widespread aridity unprecedented during the past 400 yr. We suggest that integration of hydrological and limnological approaches over space and time is needed to inform assessment of contemporary lake conditions in large, complex floodplain landscapes.

Climate-driven reductions in mid- to high-elevation snowpack and headwater glacier volume have resulted in declining flow of rivers draining the hydrographic apex of western North America during the past century (e.g., Dery and Wood 2005; Rood et al. 2005; Schindler and Donahue 2006; Barnett et al. 2008; Burn et al. 2010; Sauchyn et al. 2015; Scalzitti et al. 2016). Diminishing river discharge threatens downstream ecosystems and societies, where freshwater resources have traditionally been managed under the assumption of hydrological stationarity (Schindler and Donahue 2006; Milly et al. 2008). This assumption may, however, lead to misguided water resource planning and decision making (Milly et al. 2008), as best exemplified by numerous paleohydrological reconstructions which show there have been extended periods (decades to centuries) in the past when river discharge has been well below that experienced during the instrumental period (Watson and Luckman 2004; Wolfe et al. 2008a; Wolfe et al. 2011; Sauchyn et al. 2015; Coulthard et al. 2016). Furthermore, evidence suggests that time since European settlement has been an era of relatively abundant freshwater supply, enhanced by glacial meltwater contributions to river discharge in response to glacier expansion during the Little Ice Age (LIA; Wolfe et al. 2011). Long-term perspectives identify that this era of abundant freshwater is ending, with significant and imminent consequences for downstream ecosystems and societies (Rood et al. 2005; Schindler and Donahue 2006; Wolfe et al. 2008a; Rasouli et al. 2013).

The Peace-Athabasca Delta (PAD), northern Alberta, is one such downstream landscape that is responsive to, and heavily reliant upon, eastward-flowing river discharge originating in the Rocky Mountains to support its rich biological diversity (e.g., PADPG 1973; Prowse and Conly 1998). The PAD is recognized as a Ramsar Wetland of International Importance and contributed to the listing of Wood Buffalo National Park (WBNP), which contains 80% of the PAD, as a UNESCO World Heritage Site. River water that recharges the abundant shallow lakes and wetlands during periodic spring ice-jam floods is a crucial hydrological process for sustaining...
the ecological integrity of the delta (Prowse and Conly 1998), but the frequency of such events has been in decline for decades (Timoney et al. 1997; Timoney 2002; Wolfe et al. 2006; Wolfe et al. 2008a). For example, 2014 marked the first time in nearly 20 yr (since 1997) that widespread ice-jam flooding has occurred. The cause for declining ice-jam flood frequency has long been the subject of analysis, which has centered on identifying relative contributions of climate change and regulation of the Peace River by the WAC Bennett Dam (e.g., Prowse and Conly 1998; Wolfe et al. 2012; Beltaos 2014). Reduction of flooding has resulted in a decline of open water habitat and encroachment of willows as wetlands dry out (Timoney 2013). Concerns over lower lake and wetland water levels in the PAD have been heightened with the recent approval and onset of construction of the Site C hydroelectric dam on the Peace River, and water withdrawals from the Athabasca River to support the oil sands industry. These concerns have led to a petition submitted to UNESCO by the Mikisew Cree First Nation to place WBNP on the List of World Heritage Sites in Danger, in recognition of the multiple stressors that threaten the PAD (MCFN 2014).

A key challenge to contextualizing the effects of declining river discharge and frequency of flood events on lakes in the hydrologically dynamic PAD is that hydrometric data only span the past few decades and are sparse in spatial extent, which inhibit ability to clearly identify the causes of declining lake water levels and flood frequency within the delta. This impedes resource management decision making and stewardship. To address this pressing knowledge gap, a series of paleolimnological investigations were conducted at several lakes in the PAD during the early 2000s, which provided new insights into the evolution, variability, and drivers of lake hydrological conditions within the delta (reviewed in Wolfe et al. 2012). A central finding was the identification of complex relations among climate change, river discharge and flood frequency, and lake hydrology, which are expressed at varying spatial and temporal scales. For instance, during the LIA (~ 1600–1900 C.E.), high summer river discharge raised Lake Athabasca water levels and inundated low-lying central portions of the delta (Wolfe et al. 2008a; Johnston et al. 2010; Sinnatamby et al. 2010). Concurrently, lakes in elevated areas of the delta underwent water-level drawdown in response to local climate aridity and low frequency of ice-jam floods because of delayed and protracted upstream, high-elevation snowmelt runoff. In contrast, during the 20th century, evaporation-driven water-level drawdown has occurred at both high and low elevation areas of the PAD due to climate change and declining spring and summer river discharge. With expected continued declines in high-elevation snowpack and headwater glacier volume, Wolfe et al. (2008a) predicted that increasingly low river discharge would lead to further drying of the delta.

In the PAD, river floodwaters exert strong influence on limnological conditions of the floodplain lakes. As illustrated by Wiklund et al. (2012), floodwaters raise concentrations of suspended sediment, total phosphorus (TP), sulfate and dissolved silica (Dsi) of receiving lakes, and reduce concentrations of total nitrogen (TN), dissolved organic carbon (DOC), and most major ions. After flooding, limnological conditions respond at two timescales (Wiklund et al. 2012). One occurs over a few weeks to months as suspended sediments settle out of the water column of lakes, which increases water clarity and reduces TP concentration but without substantial change in concentration of DOC, sulfate, TN, or ions. The other timescale occurs over several years to decades, as evaporation raises concentrations of most nutrients, DOC, and ions. Thus, alteration of flood regimes has potential to alter physical and chemical characteristics of lakes in the PAD.

In light of widespread ice-jam flooding in 2014 and subsequent arid conditions in 2015, we integrate spatial and temporal data to assess current hydrological and limnological conditions in lakes of the PAD. First, we use a map produced by WBNP that marks the extent of 2014 floodwaters, supplemented by lake and river water isotope data, and water isotope and limnological data from across the delta in 2015 to show that the 2014 floodwaters had largely short-term (within-year) effects. Second, we demonstrate strong, uniform influence of evaporation during the past 15 yr on water balance at five representative lakes, a trend that began in the early to mid-20th century and is unprecedented in the context of the past ~ 400 yr. Findings strongly suggest that the delta has entered a new climate-driven regime of low water availability during the past few decades, which threatens aquatic habitat and ecological integrity.

**Methods**

**Study area and sampling locations**

The PAD spans 6000 km² and contains three distinct sectors, differentiated by the relative roles of hydrological processes that influence lake water balances (Fig. 1) (PADPG 1973; Pietroniro et al. 1999; Wolfe et al. 2007b). The northeastern Peace sector is a relic delta, which receives Peace River floodwater during infrequent high-elevation ice-jam flood events. These events can result in widespread flooding of the delta. Consequently, lakes in this region of the delta are strongly influenced by evaporation (except on occasions when they are flooded) and have been termed closed-drainage, isolated, or perched basins. The southern Athabasca sector contains both relic and active delta regions. Lakes in the relic portion of the Athabasca sector tend to be closed drainage, whereas lakes in the active portion are mainly restricted drainage, which capture a broad gradient of influence from river floodwaters. The central, low-lying portion of the delta contains broad, shallow lakes that continuously receive discharge from many rivers and creeks and are classified as open drainage. A subset of closed-drainage lakes in the central interior of the delta are termed shallow...
Fig. 1. Map showing location of the PAD, Alberta, and the location of 61 lake (black circles) and nine river (black triangles) sites within the delta sampled in 2015. Sites additionally sampled in 2014 (gray samples) and the five sediment core collection sites (circles) are noted.
rainfall-influenced lakes, as recognized by Wolfe et al. (2007b), and tend to be ephemeral.

The extent of the 2014 spring ice-jam flood was determined from flight surveys by staff of WBNP and confirmed by measurement of water isotope compositions from 16 lakes and eight river locations on 30 May 2014–03 June 2014 (Fig. 1). This information was used to categorize 61 lakes as flooded or not flooded in 2014. One large, open-drainage basin, Mamawi Lake, was sampled in two locations, one near the outlet (Chenal des Quatre Fourches; PAD 45A) and one near the inflow (Mamawi Creek; PAD 45B). These lakes (and nine river sites) were used to evaluate hydrological and limnological conditions 1 yr after the 2014 flood event based on measurements of water isotope composition and water chemistry (26–31 May 2015, 26–28 June 2015 [only water isotope composition], 27–28 July 2015, and 15–16 September 2015; Fig. 1).

To place recent water isotope data into a longer temporal perspective, sediment core records of cellulose-inferred lake water oxygen isotope composition previously published from a subset of five lakes (Wolfe et al. 2008a,b; Sinnatamby et al. 2010; Fig. 1) were assembled and combined with water isotope compositions measured periodically in the same lakes between 2000 and 2006. Three of these lakes are located in the northern Peace sector (PAD 5 [informally called “Spruce Island Lake”; Wolfe et al. 2005], PAD 9, and PAD 12) and are closed-drainage basins that, presently, receive river floodwaters infrequently. The other two lakes are located in the southern Athabasca sector (PAD 23 and PAD 31 [local name: “Johnny Cabin Pond”; Wolfe et al. 2008b]), and their hydrological conditions have been recently influenced by geomorphic changes in the flow path of the Athabasca River and its distributaries. PAD 23 is a closed-drainage basin and has infrequently received river floodwaters since engineered excavation of the Athabasca River Cut-Off in 1972. PAD 31 is a restricted-drainage basin that has frequently received river floodwater from Mamawi Creek since the Embarras Breakthrough in 1982. Further site details may be found in the original publications (Wolfe et al. 2005; Wolfe et al. 2008a,b; Sinnatamby et al. 2010).

Isotope hydrology of lakes

Water samples for oxygen and hydrogen isotope analysis were collected mid-lake (or mid-channel) from a depth of ~10 cm and stored in sealed 30 mL high-density polyethylene bottles. Lake water isotope compositions pre-2014 were measured by conventional continuous flow isotope ratio mass spectrometry (CF-IRMS), whereas 2014 and 2015 samples were measured by off-axis integrated cavity output spectroscopy (O-AICOS). For the samples measured by CF-IRMS, $\delta^{18}O$ was analyzed by 2% CO$_2$ headspace equilibration on a multi-flow coupled with GV instruments Isoprime (MF-GVI-Isoprime) and $\delta^2$H was analyzed by hot chromium reduction on a High Temperature Euro Vector EA coupled with GV Instruments Isoprime (HT-EA-Isoprime). For the samples measured by O-AICOS, a Los Gatos Research Triple Liquid Water Isotope Analyzer (LGR T-LWIA 45-EP) was used. All samples were analyzed at the University of Waterloo—Environmental Isotope Laboratory (UW-EIL). Isotope compositions are expressed as $\delta$-values, representing deviations in permil ($\%_{oo}$) from Vienna Standard Mean Ocean Water (VSMOW) such that $\delta_{\text{sample}} = [(R_{\text{sample}}/R_{\text{VSMOW}}) - 1] \times 10^3$, where $R$ is the $^{18}O/^{16}O$ or $^2H/^{1}H$ ratio in the sample and VSMOW. Results of $\delta^{18}O$ and $\delta^2$H analyses are normalized to $-55.5\%_{oo}$ and $-428\%_{oo}$ respectively, for Standard Light Antarctic Precipitation (Coplen 1996). Analytical uncertainties are $\pm 0.2\%_{oo}$ for $\delta^{18}O$ and $\pm 2.0\%_{oo}$ for $\delta^2$H for samples analyzed by CF-IRMS, and $\pm 0.2\%_{oo}$ for $\delta^{18}O$ and $\pm 0.8\%_{oo}$ for $\delta^2$H for those analyzed by O-AICOS.

To identify the hydrological processes controlling lake–water balances at the individual lake and landscape scale, a coupled-isotope tracer approach was used (Yi et al. 2008) based on the classic linear resistance model (Craig and Gordon 1965). Initially, an isotope framework representing average conditions from 2000 to 2015 was developed using techniques similar to those described in Wolfe et al. (2007b) and Yi et al. (2008) for the PAD. The isotope framework provides a semi-quantitative method of assessing the water balance of rivers and lakes during the ice-free season.

The isotope framework consists of two linear trends in $\delta^{18}O$–$\delta^2$H space, which are the result of mass-dependent partitioning of stable isotopes $^{1}H_2^{16}O$, $^{1}H_2^{18}O$, and $^{1}H_2^{2}H$ within the hydrological cycle (Edwards et al. 2004). The isotope composition of precipitation at a site will cluster along a local meteoric water line (LMWL), which often lies close to the global meteoric water line (GMWL). The GMWL represents the observed relation between $\delta^{18}O$ and $\delta^2$H in amount-weighted annual precipitation worldwide, described by $\delta^2H = 8 \delta^{18}O + 10$ (Craig 1961). For the PAD, the LMWL is approximated by $\delta^2H = 6.7 \delta^{18}O - 19.2$, based on precipitation collected at Fort Smith, NWT (Wolfe et al. 2007b).

The isotope composition of local surface water fed by mean annual isotope composition of precipitation ($\delta_p$) undergoing evaporation will plot in a linear cluster offset from the LMWL, forming a linear trend called the local evaporation line (LEL) (Gibson and Edwards 2002). Movement of lake and river water samples up the LEL occurs due to isotopic enrichment and indicates increasing influence of evaporation and the resulting heavy isotope build-up in remaining surface water. Enrichment of $^{18}O$ and $^2$H in evaporating waterbodies is described by the linear resistance model of Craig and Gordon (1965), which can be combined with local hydroclimate data (temperature and relative humidity, isotope composition of ambient atmospheric moisture) to predict the trajectory of the LEL (Gibson and Edwards 2002; Edwards et al. 2004; Wolfe et al. 2007b; Gibson et al. 2016). This is advantageous to the more common technique of applying linear regression through measured
lake water isotope compositions, because lake water isotope compositions can be interpreted independently based on their position along (degree of evaporation) and about (i.e., above/below; relative influence of different input waters such as snowmelt and rainfall) the LEL.

For the PAD, average ice-free season flux-weighted relative humidity and temperature were calculated for the period of 2000–2015 using Thornthwaite (1948) and climate data from Environment Canada (station number 71305; www.climate.weather.gc.ca) and the National Research Council of Canada (http://www.nrc-cnrc.gc.ca/eng/services/sunrise/). Important features of the LEL include the mean annual isotope composition of precipitation ($\delta_{\text{SSL}}$), the steady-state isotope composition for a terminal basin ($\delta_{\text{SSL}}$), which represents the special case of a lake at hydrologic and isotopic steady state in which evaporation exactly equals inflow, and the limiting non-steady-state isotope composition ($\delta^*$), which indicates the maximum potential isotopic enrichment of a lake as it approaches complete desiccation. A well-suited index lake known to be in isotopic steady-state was used to determine $\delta_{\text{SSL}}$ and atmospheric moisture for the ice-free season ($\delta_{\text{ASL}}$) (Yi et al. 2008), while $\delta^*$ was calculated using Gonfiantini (1986). See Supporting Information for calculations to determine the LEL.

The 2000–2015 PAD isotope framework was then used to calculate evaporation to inflow (E/I) ratios, an index of lake-water balance described by Gibson and Edwards (2002) and others. As in many regional studies that have used this approach (e.g., Brooks et al. 2014; Gibson et al. 2017; MacDonald et al. 2017), we compare E/I ratios across a large number of lakes to differentiate regions of the delta. E/I ratios were calculated as:

$$E \Bigg( \frac{\delta_{\text{I}} - \delta_{\text{L}}}{\delta_{\text{E}} - \delta_{\text{L}}} \Bigg)$$

where $\delta_{\text{E}}$ is the isotope composition of evaporative flux (Craig and Gordon 1965), $\delta_{\text{L}}$ is the lake water isotope composition, and $\delta_{\text{I}}$ is the isotope composition of input waters to the lake (see Supporting Information). E/I ratios determined from 2015 lake water isotope data were interpolated across the delta surface by ordinary kriging using ArcMap 10.3 software. Because the model becomes increasingly unrealistic when E/I ratios exceed 1.5, we set this as a maximum value to differentiate the lakes experiencing strong non-steady state conditions.

**Limnology**

In situ measurements of limnological parameters (pH, specific conductivity) were measured using YSI ProDSS sondes and water depths were measured using a plumb-bomb. At each site, 5 L of water were collected from ~ 10 cm depth for water chemistry analysis. Samples were refrigerated until filtration later that day or the following day. Coarse-filtered (80-µm mesh) lake water was used for analysis of TN and TP, while sub-samples for analysis of total dissolved nitrogen (TDN), total dissolved phosphorus (TDP), DSI, dissolved inorganic carbon (DIC), DOC, and major ions were passed through Sartorius cellulose acetate filters (0.45 µm). Major cations were preserved using nitric acid. For analysis of chlorophyll a (Chl a), water samples were passed through Whatman GF/F filters, which were kept frozen until analysis. Samples were analyzed at the University of Alberta’s Biogeochemical Analysis Services Laboratory (TN, TP, TDN, TDP, DSI, DIC, DOC, major ions) or the University of Waterloo (Chl a).

Principal components analysis (PCA) was used to determine whether limnological effects of floodwaters to lakes during spring 2014 persisted into the 2015 ice-free season, as expected based on Wiklund et al. (2012). The PCA was performed on limnological data from 56 lakes that did not flood during 2015, determined primarily on water isotope data. Six of the 62 lake sites were removed from the analysis because their 2014 flood status was uncertain (PAD M1, PAD M2, PAD M3, PAD M4, PAD M5, PAD M6). All nine river sites and four of the lake sites with continuous or near-continuous river channel connections (PAD 45A, PAD 45B, PAD 62, PAD 63) were included passively in the PCA to provide a reference for limnological conditions of lakes receiving floodwaters, without influencing the relative positions of the sample scores for the lakes that were not flooded in 2015. PAD 54 was also included as a passive sample, because it flooded again in spring 2015 based on isotopic and limnological overlap with river sites, a feature which confounds the ability to detect if limnological effects of the 2014 flood persisted through 2015. In this way, PAD 54 also serves as a useful reference for expected river floodwater-influenced limnological conditions in the absence of 2014 limnological data. Thus, PCAs were run with 51 lake sites as active samples. Limnological variables were natural-log transformed. In the PCAs, scaling focused on inter-sample distances, variable scores were divided by their standard deviation, and variables were centered and standardized. Sample scores for lakes were coded in PCA plots according to whether or not they flooded during the ice-jam flood of 2014. All water chemistry variables listed above were included as active variables in the PCAs, except for $\delta^{18}$O which was included passively to assess influence of floodwaters and evaporation on water chemistry of lakes. Analysis of similarities (ANOSIM) tests were conducted on the 51-lake dataset to determine if water chemistry in May 2015, July 2015, and September 2015 differs significantly between lakes that flooded in spring of 2014 and those that did not flood. The PCA was performed using CANOCO version 4.5 (ter Braak and Smilauer 2002) and the ANOSIM tests were run using R (R Core Team 2017), RStudio (RStudio Team 2016), and the vegan package (Oksanen et al. 2017).

**Isotope paleohydrology**

Cellulose-inferred lake water oxygen isotope reconstructions, spanning the past 200–400 yr, were derived from
Results

The 2014 ice-jam flood event

Extensive overland flooding of the PAD occurred for about a week between 03 May 2014 and 10 May 2014, when ice-jams formed on the Peace and Athabasca rivers (Straka and Gray 2014; Fig. 2a). Maximum water level rise (an estimated 6 m) on the Peace River occurred around 05–06 May, which inundated substantial low-lying portions of the Peace sector of the delta. The north and south banks of the Peace River were breached in several areas and major channels south of the Peace River carried floodwater into the delta. An ice-jam on the Quatre Fourches channel was reported to form and persist during 07–10 May, which resulted in flooding in this area. In the Athabasca sector, much of the area between the Athabasca and Embarras rivers, as well as south of the Athabasca River, were inundated with floodwater. Water levels rose as much as 4 m on the Embarras River and Mamawi Creek, causing some overbank flooding in this region.

The river and lake water isotope compositions measured at 16 lakes and eight river sites in May 2014 were plotted on a δ18O-δ2H graph to determine whether the lakes received river floodwaters, and were then compared with the aerial extent of flooding mapped by WBNP staff (Fig. 2a,b). The Peace River is isotopically depleted and plots below the LEL in both sampling locations, as expected given the influence of snowmelt on the spring river water isotope composition. The Rivière des Rochers also plots below the LEL, suggesting flow reversal may have occurred in this channel causing floodwater from the Peace River to be carried south. Similarly, the Embarras River in the Athabasca sector plots below the LEL, likely as a result of receiving floodwater from the isotopically depleted Athabasca River. Prairie River, which flows between Mamawi Lake and Lake Claire, was sampled in two locations, both of which plot along the LEL, indicating some influence of evaporation. This is likely due to the inflow of evaporatively enriched lake water from Lake Claire and Mamawi Lake to this channel.

For most lakes sampled in spring (May) 2014, water isotope compositions plot at the lower, isotopically-depleted end of the LEL, in the range of values for the Peace River, Rivière des Rochers, and Embarras River, indicating that these lakes received river floodwaters. Exceptions include PAD 18, PAD 47 (Hilda Lake), and PAD 61 (Sonny’s Lake), which were isotopically enriched due to greater influence of evaporation in the absence of river flooding (Fig. 2b). Observations indicated that all three of these lakes were not turbid at the time of sampling, also consistent with having not received river floodwaters (Yusuf 2015). The isotope-inferred flood status of the lakes is in agreement with the flood extent mapped by WBNP staff, except for PAD 9. This lake, located in the southern portion of the Peace sector, lies outside of the mapped flood extent (Fig. 2a) but is strongly isotopically depleted suggesting it likely received river floodwater (Fig. 2b). Observations of nearby overland flooding and high-water levels made by the sampling crew during the aerial survey and water isotope sample collection on 1st June 2014, suggest that floodwaters entered this lake.

Hydrological conditions during 2015

In May 2015, lakes that flooded and lakes that did not flood in 2014 show separation of isotope compositions along the LEL (Fig. 3a). Isotope compositions of most of the lakes that flooded in 2014 are more isotopically depleted, plotting lower on the LEL. Four lake sites (PAD 45B, PAD 54, PAD M5, PAD M6) plot below the LEL, in the range of the river sites, indicating contribution of river water into these basins. The lakes that were not flooded in 2014 typically plot higher along the LEL, closer to δSSL, suggesting greater influence of evaporation in the absence of river flooding. By June 2015, the separation between flooded and non-flooded lakes diminishes as evaporation caused isotope composition of most of the lakes that were flooded in 2014 to move up the LEL and overlap with the non-flooded lakes. The most isotopically enriched lakes (PAD 19, PAD 20, PAD 21) were not flooded in 2014. As the ice-free season progresses and lakes experience increasing evaporation, the isotope compositions of 2014 flooded and non-flooded lakes become increasingly tightly clustered and continue to move up the LEL due to greater influence of atmospheric parameters (isotope composition of atmospheric moisture, temperature, relative humidity) on the lake-water isotope compositions with increasing influence of evaporation. Exceptions are the few lakes in the low-lying central portion of the delta that receive continuous river input and, thus, remain isotopically depleted throughout the ice-free season. By September 2015, lakes are clustered along the LEL and many lakes from both 2014 non-flooded and flooded categories plot between δSSL.
Fig. 2. (a) The extent of 2014 spring flooding as mapped by WBNP staff is shown in light blue (Straka and Gray 2014). Note that the extent of floodwaters east of the WBNP boundary (east of Fletcher Channel) was not mapped. Sites sampled in 2015 are coded according to whether they were flooded in spring of 2014 (dark blue), not-flooded (red), or flood status unknown (black). Hydrological coding is based on location primarily, as well as isotope data where available. (b) $\delta^{18}$O-$\delta^{2}$H graph showing the water isotope values from lakes and rivers sampled in May 2014, color-coded as flooded (blue) or not flooded (red) in spring of 2014.
Inconsequential effects of 2014 flooding

and $\delta^*$, indicating strong influence of evaporation on lake water balance.

To compare the extent of flooding in 2014 to the spatial patterns of isotopic enrichment in 2015, calculated $E/I$ ratios were interpolated across the PAD (Fig. 4). Moran’s I coefficient calculated for the $E/I$ ratios during sampling periods show moderate spatial association (May: Moran’s $I = 0.305$, $p < 0.001$; June: Moran’s $I = 0.344$, $p < 0.001$; July: Moran’s $I = 0.442$, $p < 0.001$; September: Moran’s $I = 0.350$, $p < 0.001$). In May 2015, lakes in the central area of the Peace sector around the Chenal des Quatre Fourches, which was extensively flooded in 2014, had relatively low $E/I$ ratios (0.3–0.5). The northwestern portion of the Peace sector, which experienced some flooding in 2014, had relatively low $E/I$ ratios (0.3–0.5).
Fig. 4. Maps showing spatial interpolation (by ordinary kriging) of evaporation-to-inflow (E/I) ratios for 61 lakes across the PAD in May 2015, June 2015, July 2015, and September 2015, the year after an extensive ice-jam flood event. Overlaid is the 2014 flood extent map from Fig. 2a.
the Peace sector, which was not flooded in 2014, had higher E/I ratios (0.7–1.1). Lower E/I ratios in the central portion of the Peace sector compared to the northwestern and northeastern portions in May 2015 could be a result of lasting effects of the 2014 flooding in this area or river water input into the low-lying central area during May 2015, although we have no field observations to support the latter. As early as June 2015, E/I ratios in the areas of the Peace sector that were flooded in 2014 were comparable to those areas that were not flooded. By July and continuing in September, E/I ratios were > 1.0 across most of the Peace sector. Only some lakes in the northern reaches of the Chenal des Quatre Fourches, closest to the Peace River, possessed E/I ratios < 1.0 in September 2015.

In the Athabasca sector, lakes in the southeastern and central portions that were extensively flooded in 2014 had low E/I ratios (0.3–0.6) in May 2015. The non-flooded southwestern area had higher E/I ratios in May (0.7–1.2). E/I ratios in the flooded (2014) areas of the Athabasca sector increased by June (0.7–0.9) and remained high for the rest of the ice-free season. By June 2015, the non-flooded southwestern area also experienced an increase in E/I ratios to > 1.0. Low-lying areas in the central and southeastern portions of the Athabasca sector may be displaying lasting effects of the 2014 flood, although this is difficult to distinguish from “normal” hydrological conditions in the delta as this area generally receives continuous river inflow under both flood and non-flood conditions. Notably, the highest E/I ratios were in the elevated northeastern portion of the Peace sector and the southwestern portion of the Athabasca sector, which were outside of the extent of the spring flood of 2014 and likely have not received river floodwater for many decades, implying that the high E/I ratios in 2015 are a continuation of long-term seasonal evaporative water loss.

**Limnological conditions during 2015**

For all three limnological sampling episodes in 2015 (May, July, September), PCAs capture similar amounts of variation along the first two axes (May: AX1 = 36.5%, AX2 = 17.6%, Total = 54.1%; July: AX1 = 32.5%, AX2 = 18.5%, Total = 51.0%; September: AX1 = 37.8%, AX2 = 16.2%, Total = 54.0%), and vectors of the water chemistry variables show consistent associations with the first two axes (Fig. 5). PCA axis 1 captures mainly a gradient of ionic content, whereas axis 2 captures mainly gradients of pH and concentrations of nutrients, DOC, and sulfate. Sample scores for the river sites (black triangles in Fig. 5), included passively in the PCAs, are positioned to the right along PCA axis 1 and high on PCA axis 2, indicating relatively high turbidity and high concentrations of SiO₂, Na, SO₄, and Cl, and relatively low concentrations of K, DOC and nutrients (TP, TDP, TN, TDN) and low δ¹⁸O. Passive sample scores for the three open-drainage lakes (blue squares; Lake Clair [PAD 62], Lake Athabasca [PAD 63], and Mamawi Lake [PAD 45A/B]) cluster near the river sites, indicating that continuous to near-continuous river inflow strongly influences their water chemistry. PAD 54, also included passively, is consistently positioned with the river sites for all three sampling episodes, because it was flooded in May 2015. Sample scores for the lakes that flooded in 2014 and the non-flooded lakes are positioned lower on the second axis than the rivers.
indicating relatively lower turbidity and lower concentrations of Na, SO₄, and Cl, but higher concentrations of DOC, nutrients (TP, TDP, TN, TDN), and higher δ¹⁸O. Both flooded (2014) and non-flooded lakes are also scattered along axis 1, indicating a range of conductivity, DIC, and ionic content. The high degree of overlap of sample scores throughout the 2015 season for lakes that flooded and did not flood in 2014 suggests that limnological effects of the 2014 flood did not persist to 2015. The one exception may be PAD 15, which was flooded in 2014 and has similar limnological characteristics as the river sites during 2015. However, dilute water chemistry at PAD 15 may also have been influenced by snowmelt given that its isotope composition plots well below the LEL (Fig. 3). ANOSIM tests confirm that water chemistry conditions do not differ significantly (p > 0.05) during any of the months sampled in 2015 between lakes that flooded and those that did not flood in 2014 (May: R = 0.095; July: R = 0.058; September: R = 0.057).

**Paleohydrological records**

To provide temporal context for contemporary lake hydrological conditions, cellulose-inferred lake water δ¹⁸O (δ¹⁸Oₗw) records spanning the past ~ 200–400 yr were assembled from five lakes along with directly measured mean ice-free season lake water δ¹⁸O values from 2000 to 2006 and 2014 to 2015 (Fig. 6).

During the LIA (1600–1900), the δ¹⁸Oₗw records of the five lakes reflect different hydrological conditions depending on their physiographic settings (Fig. 6). The most elevated basin, PAD 5, displays varying but isotopically-enriched values (~ −13‰ to −3‰) that occasionally exceed δSSL, consistent with evidence for periodic desiccation due to locally arid climate (Wolfe et al. 2005; Wolfe et al. 2008a). In contrast, low-lying basins (PAD 9, PAD 12, PAD 31) possess low δ¹⁸Oₗw values (~ −20‰ to −14‰) because they were all variably flooded by isotopically depleted water from Lake Athabasca (modern δ¹⁸O = −17‰ to −15‰) and the Rivière des Rochers, which rose by as much as 2.3 m due to increased supply of glacial meltwater to the Peace and Athabasca rivers during summer (Wolfe et al. 2008a; Johnston et al. 2010; Sinnatamby et al. 2010). Although PAD 23 was likely south of the margin of the Lake Athabasca LIA highstand, low δ¹⁸Oₗw values (~ −20‰ to −15‰) suggest it was strongly influenced by Athabasca River floodwaters.

Gradual increase in δ¹⁸Oₗw values in the Peace sector lakes (PAD 5, PAD 9, PAD 12) suggests increasing role of evaporation post-LIA (i.e., after 1900). These trends reflect decline in ice-jam flood frequency and Lake Athabasca water level due to reduction in high-elevation snow and glacial contributions to river discharge (Wolfe et al. 2006; Wolfe et al. 2008a; Wolfe et al. 2011), which is also evident in shorter hydrometric records of rivers draining the hydrographic apex of North America (e.g., Dery and Wood 2005; Rood et al. 2005; Schindler and Donahue 2006; Barnett et al. 2008; Burn et al. 2010; Sauchyn et al. 2015; Scalzitti et al. 2016). Locally decreasing relative humidity (Wolfe et al. 2008b) and possibly a longer-ice free season also contribute to these trends. For the Athabasca sector lakes, anthropogenic and natural changes in the flow of the Athabasca River and distributaries are responsible for the contrasting late 20th century δ¹⁸Oₗw trends at PAD 23 and PAD 31 (Wolfe et al. 2008b). Sharply increasing δ¹⁸Oₗw at PAD 23 after 1970 is due to the engineered Athabasca River Cut-Off, which reduced the propensity of ice-jam flooding in the vicinity of PAD 23. In contrast, the decline and more variable δ¹⁸Oₗw at PAD 31 after 1980 is due to the Embarras Breakthrough, which redirected substantial flow from the Embarras River to Cree and Mamawi creeks leading to increased flooding in this area.

During the past 15 yr when we have direct measurements of lake water δ¹⁸O, all lakes with the exception of PAD 5 possess values higher than at any time during the paleohydrological records. PAD 9, PAD 12, and PAD 23 lake water δ¹⁸O values approach, and occasionally exceed, the critical threshold of δSSL. Likewise, PAD 5 lake water δ¹⁸O values hover near δSSL, having only been higher during the LIA. Based on our field observations, an increasing and persistent role of evaporation has led to marked declines in water level at PAD 5 and PAD 9 during the past decade, despite apparent floodwaters reaching PAD 9 in 2014 (Fig. 7). Even recent (i.e., post-1982 Embarras Breakthrough) river floodwater “buffering” of PAD 31, including during 2014, appears to be waning given the evidence of generally higher lake water δ¹⁸O values at this lake (Fig. 6).

**Discussion**

Despite extensive flooding of the PAD in May 2014, analysis of water isotope compositions and limnological variables in 2015 indicated only short-lived, mostly within-year effects of the 2014 flood. By as early as June 2015, lakes that were both flooded and not flooded in 2014 were isotopically enriched to a similar extent due to evaporation, and little hydrological distinction existed between these two groups. Although the central portion of the Peace sector and southeastern portion of the Athabasca sector were most strongly influenced by flooding in 2014, E/I ratios during June 2015 were already greater than 0.5 indicating strong evaporative influence.

Limnological data support the short-lived isotope-inferred hydrological effects of the 2014 flood. By May 2015, water chemistry conditions did not differ significantly between lakes that flooded and lakes that did not flood in 2014 (with the exception of PAD 15). Although we do not have water chemistry from 2014 to verify the effects of flooding on limnological conditions in spring 2014, previous research by Wiklund et al. (2012) has shown that flooded lakes have similar water chemistry characteristics as river water. This effect is evident in PAD 15 (which flooded in May 2014 but not
2015) and PAD 54 (flooded in May of 2014 and 2015), and thus both lakes possess water chemistry characteristics that overlap with river sites throughout the 2015 ice-free season (Fig. 5). The short-lived effects of flooding on limnological conditions on the other lakes that flooded in 2014 was surprising, because Wiklund et al. (2012) observed that infrequently flooded lakes in the Peace and Athabasca sectors of the delta took multiple years after a flood to return to typical closed-drainage limnological conditions characterized by high concentrations of DOC, TKN, bio-available nutrients and ions, and low concentrations of suspended sediments and $\text{SO}_4$. In contrast, we found that the magnitude of evaporative water loss during the remainder of the 2014 post-flood ice-free season and early 2015 ice-free season leading up to our sampling in May 2015 resulted in a more rapid than predicted return to limnological conditions typical of those found during long periods (many years to decades) without flooding.

The flood-pulse concept, as applied to river floodplain lakes, postulates that river flooding acts to homogenize limnological conditions, followed by increasing heterogeneity during the post-flood period (Junk et al. 1989; Tockner et al. 2000; Junk and Wantzen 2004). Here, we find a situation where the post-flood period appears to have been truncated.
by the strong influence of evaporation. This agrees with model predictions that lakes in the Mackenzie Delta, downstream of the PAD, will become increasingly sensitive to local climate conditions as frequency and magnitude of flooding decreases (Marsh and Lesack 1996). We suspect that cumulative effects of long-term and ongoing decline in frequency and magnitude of river flooding, and arid conditions, are the dominant influence on the hydrological and limnological trajectory of lakes in the PAD, which, apparently is now unlikely to be altered by a single and isolated large flood event.

Isotope paleohydrological records provide coherent evidence of multi-decadal drying of lakes in the PAD. In the northern Peace sector, this began after the conclusion of the LIA during the early to mid-20th century. In the southern Athabasca sector, engineered and natural changes in flow of the Athabasca River and distributaries have had profound influence on hydrological conditions of lakes, but trends toward drier conditions (i.e., higher measured lake-water $\delta^{18}O$ values) are now evident even along a redirected river flow path as observed at low-lying PAD 31. Indeed, in four of the five paleohydrological records, the highest lake water $\delta^{18}O$ values (i.e., greatest evaporative isotopic enrichment) during the past 200–400 yr has occurred during the recent monitoring period. We acknowledge that direct comparison of time-integrated cellulose-inferred lake water $\delta^{18}O$ and annual averages of directly measured lake water $\delta^{18}O$ may be affected by seasonal offsets due to algal growth during the early ice-free season when lake water $\delta^{18}O$ tends to be lower, or small uncertainties in the cellulose-water oxygen isotope fractionation factor. However, neither are likely explanations for the recent observed trends in lake water $\delta^{18}O$. For example, unequivocal evidence of lake-level lowering at PAD 5 and PAD 9 (Fig. 7) is consistent with trends depicting strong influence of evaporation during recent decades.

In the PAD, some have attributed long-term drying mainly to river regulation by the WAC Bennett Dam in 1968, which has clearly altered the flow regime of the Peace River (Peters and Prowse 2001). As recently as in the past year, such statements were made by the UNESCO reactive monitoring mission (WHC/IUCN 2017) in response to the MCFN (2014) petition. However, in the northern Peace sector of the delta, most proximal to the Peace River (PAD 5, PAD 12), increasing influence of lake evaporation, evident in Fig. 6 and other proxy indicators from these lakes (Wolfe et al. 2005; Wolfe et al. 2008a), began soon after the end of
the LIA, well before the dam became operational. Sediment records from other lakes in the PAD also indicate that flood frequency and magnitude began to decline in the late 1800s (Wolfe et al. 2006). While PAD 5 desiccated during the LIA, water has persisted in PAD 9 for at least the past 1000 yr (Wolfe et al. 2008a). Substantial lake-level drawdown (~0.5–1.0 m) since the early 2000s is now visible at PAD 5 and PAD 9 (Fig. 7). Although lake-level changes in low-lying riverine environments can be extremely heterogeneous, our spatial assessment of lake water balances across the delta suggests that conditions at PAD 5 and PAD 9 are reflective of a landscape-wide trend of rapidly declining water availability during the past decade. Increasing evaporation during the past few decades recorded by the PAD 23 sediment record is unlikely to be caused by construction of the WAC Bennett Dam. PAD 23 is the most distal site from the Peace River on our transect and dredging of the nearby Athabasca River Cut-Off in 1972, which straightened the course of the river and reduced the likelihood of ice-jams developing at this location, is a primary cause for drying at this location (Wolfe et al. 2008b).

Climate-driven drying of northern shallow lakes is not unique to the PAD. Smith et al. (2005) identified widespread late 20th century decline in lake abundance and area in Siberia. Smol and Douglas (2007) observed drying of shallow lakes in the Canadian High Arctic, previously permanent waterbodies for millennia. In Alaska, studies have revealed that there has been a reduction in area and number of ponds during the late 20th century (Riordan et al. 2006). Carroll et al. (2011) utilized satellite data to show that a net reduction in lake surface area of more than 6700 km² occurred in the Canadian Arctic from 2000 to 2009. Bouchard et al. (2013) determined that lakes in low-relief, open tundra catchments are particularly vulnerable to drying when snowmelt runoff is low and identified that recent desiccation of a shallow lake in the Hudson Bay Lowlands (Canada) may be unprecedented during at least the past 200 yr. While mechanisms leading to drying of northern lakes may vary across these landscapes (e.g., permafrost thaw and lake drainage, decline in snowmelt runoff, increase in evaporation, decline in river discharge), and these need to be evaluated with due consideration of the regional context, this does appear to be a widespread consequence of climate change in northern regions.

**Concluding comments**

Here, we integrate spatial and temporal data to determine that widespread ice-jam flooding in May 2014 had largely within-year effects on hydrological and limnological conditions in lakes of the PAD, which we attribute to a multi-decadal trend of increasing evaporative influence across the landscape. Climate change since the end of the LIA has led to reduction in mid- to high-elevation snowpack and headwater glacier volume, and thus lower river discharge. These factors have conspired to produce clear evidence of rapidly declining freshwater availability in the delta, perhaps unprecedented in scale during the past 400 yr, and this firmly entrenched trajectory of change is such that a single ice-jam flood event is insufficient to mitigate these effects.

Despite their global importance, inland freshwater ecosystems may be among the most threatened, as they are particularly vulnerable to the combination of climate change and increasing impairment by human development and upstream activities (e.g., Gleick 2003; Woodward et al. 2010; Dudgeon et al. 2006). High-latitude freshwater landscapes, which are experiencing some of the fastest rates of warming (Hassan et al. 2005) and are often downstream of human activity (Gleick 2003; Schindler and Smol 2006), have unique ability to act as “sentinel systems” (Woodward et al. 2010) and provide an early warning signal of hydroecological change. Hydrologists and ecologists increasingly recognize the need to understand connectivity in ecosystems, especially for “riverscapes” (Tetzlaff et al. 2007). However, the spatial and temporal scales of hydroecological research have often been too short and too narrowly defined to adequately capture landscape-scale connectivity among freshwater ecosystems (rivers, channels, wetlands, lakes), such that the importance of these connections has been poorly characterized (Fausch et al. 2002). To understand how variability in climate and hydrological conditions affect the ecological integrity and connectivity of freshwater landscapes, research needs to encompass appropriate spatial and temporal scales (Fausch et al. 2002). Here, we used hydrological, limnological, and paleolimnological approaches to generate multiple datasets across space and time, which served to comprehensively assess the current status of hydroecological conditions in a large floodplain landscape. These results have important implications for management of the delta, as they highlight widespread long-term drying is reducing the hydrological and limnological heterogeneity of the landscape. Furthermore, they address recommendations for the PAD listed in the recent WHC/IUCN (2017) report, which include to (1) establish adequate baseline information to enhance the reference for monitoring (as demonstrated by our paleohydrological records), (2) expand the scope of monitoring (which we suggest should include continued use of water isotope tracers, along with strategic sampling for water chemistry, to track rapidly shifting lake water balances over space and time), and (3) recognize the interaction of the ecosystem and climate (demonstrated here via assembling multiple records and observations over sufficient spatial and temporal scales). Despite the challenges of generating these datasets, especially in remote northern landscapes, the value of such approaches cannot be understated as science attempts to address increasingly complex water-related problems.
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Conflict of Interest

None declared.

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