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Characterizing the Hydrology of Shallow Floodplain Lakes in the Slave River Delta, NWT, Canada, Using Water Isotope Tracers

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Abstract

The relative importance of major hydrological processes on thaw season 2003 lakewater balances in the Slave River Delta, NWT, Canada, is characterized using water isotope tracers and total suspended sediment (TSS) analyses. A suite of 41 lakes from three previously recognized biogeographical zones—outer delta, mid-delta, and apex—were sampled immediately following the spring melt, during summer, and in the fall of 2003. Oxygen and hydrogen isotope compositions were evaluated in the context of an isotopic framework calculated from 2003 hydroclimatic data. Our analysis reveals that flooding from the Slave River and Great Slave Lake dominated early spring lakewater balances in outer and most mid-delta lakes, as also indicated by elevated TSS concentrations (>0.01 g L^{-1}). In contrast, the input of snowmelt was strongest on all apex and some mid-delta lakes. After the spring melt, all delta lakes underwent heavy-isotope enrichment due to evaporation, although lakes flooded by the Slave River and Great Slave Lake during the spring freshet continued to be more depleted isotopically than those dominated by snowmelt input. The isotopic signatures of lakes with direct connections to the Slave River or Great Slave Lake varied throughout the season in response to the nature of the connection. Our findings provide the basis for identifying three groups of lakes based on the major factors that control their water balances: (1) flood-dominated ($n = 10$), (2) evaporation-dominated ($n = 25$), and (3) exchange-dominated ($n = 6$) lakes. Differentiation of the hydrological processes that influence Slave River Delta lakewater balances is essential for ongoing hydroecological and paleohydrological studies, and ultimately, for teasing apart the relative influences of variations in local climate and Slave River hydrology.

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Introduction

The Slave River Delta (SRD) is a highly productive ecosystem located on the south shore of Great Slave Lake, NWT, Canada. Flood events from the Slave River supply water and nutrient-rich sediment to delta lakes, which is believed to be important for maintaining extensive shoreline habitat and overall vitality of this northern ecosystem (English et al., 1997; Prowse et al., 2002). In recent years, increased recognition of the potential impacts of multiple stressors on SRD hydroecology, including climate variability and regulation of the Peace River upstream for hydroelectric production by the WAC Bennett Dam (Fig. 1), have raised concerns regarding the current state of the ecosystem. These concerns have implications for management of the delta and for residents of the nearby community of Fort Resolution, who utilize the delta's natural resources. However, there is limited scientific knowledge of the hydroecology of the delta and of the potential impacts of changes in climate and river discharge. Further complications arise because hydrometric and climatic records are insufficient in duration to clearly explore relationships between apparent drying of the delta over the past few decades (Bill et al., 1996; English et al., 1997) and potential causes (e.g., lower river discharge, reduced flood frequency, natural deltaic evolution, and climate variability and change). Thus, the relative roles of various driving forces on hydroecological conditions of the SRD remain largely uncertain (Prowse et al., 2002).

At a more fundamental level, key questions exist regarding the basic functioning of the SRD ecosystem. For example, no previous studies have been conducted on the water balances of the hundreds of lakes and wetlands that populate the delta, yet the maintenance of water in these basins provides habitat for significant wildlife populations. Variation of lakewater balances over seasonal and longer time scales is essentially unknown, as is the relative importance of various hydrological processes. These processes include precipitation, snowmelt runoff, river flooding, Great Slave Lake seiche events, and evaporation.

As part of ongoing multidisciplinary research to assess contemporary and past hydroecological conditions in the SRD (Wolfe et al., 2007a), we are using water isotope tracers (^{18}O, ^{2}H) to examine the roles of major hydrological processes on lakewater balances. Here we interpret results from lake and river sampling conducted during the 2003 ice-free (thaw) season. Stable isotope tracers offer an effective method to assess controls on lakewater balances because isotopic partitioning in the hydrological cycle is well understood and a rapid survey of many basins at a single point in time can be acquired without the need for field-intensive, site-specific investigations (see Edwards et al., 2004). This technique has been used extensively in hydrological studies to characterize spatial and temporal variability in the water balances of lakes in other remote regions of northern Canada (e.g., Gibson, 2001, 2002; Gibson and Edwards, 2002), including the Peace-

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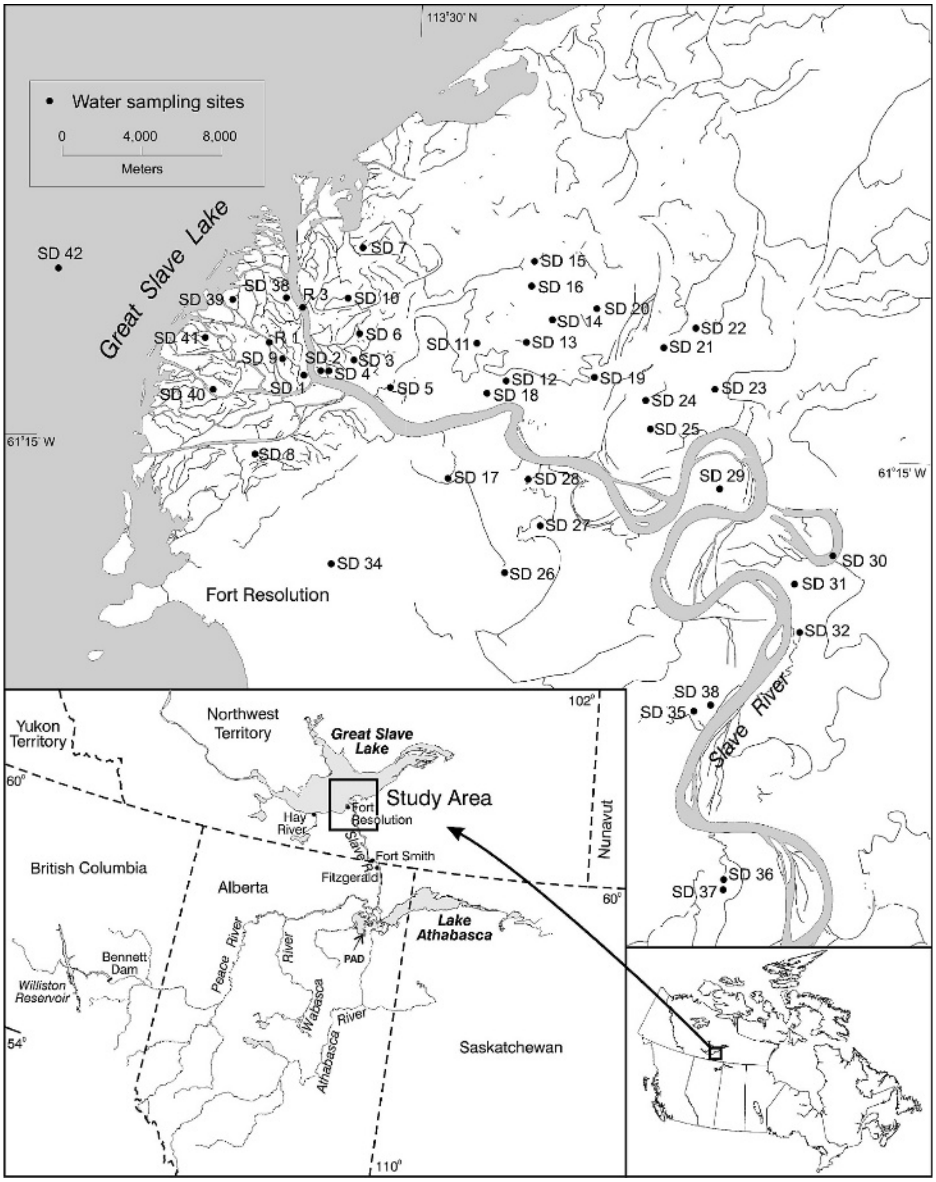

FIGURE 1. Location of the Slave River Delta, NWT, Canada, including lake and river sampling sites.

Athabasca Delta, a similar riparian ecosystem upstream of the SRD (Wolfe et al., 2007b).

As discussed in detail below, the main sources of water for SRD lakes—snowmelt, rain, the Slave River, and Great Slave Lake—each possess characteristic isotopic signatures. This feature, in addition to subsequent heavy-isotope enrichment during evaporation, is used to characterize the relative importance of key hydrological processes on SRD lakewater balances against the backdrop of an isotope framework developed from hydroclimatic conditions that prevailed during 2003. Furthermore, spatial mapping offers insight into the relative importance of these hydrological processes across local landscapes of the SRD. Such knowledge is critical for constraining reconstructions of past hydrological conditions and predicting hydrological responses of the SRD ecosystem to natural and anthropogenic changes in climate and river discharge characteristics.

The Slave River Delta

The SRD (61°15′N, 113°30′W) began to form during the retreat of the Keewatin Sector of the Laurentide Ice Sheet and the drainage of Glacial Lake McConnell at ca. 8070 ^{14}C yr BP (Vanderburgh and Smith, 1988). Relict deltaic and alluvial sediments cover approximately 8300 km^2 (Vanderburgh and Smith, 1988) and extend along the Slave River 180 km downstream from Fort Smith, NWT, to the active delta. Currently, the active portion of the SRD spans approximately 400 km^2 (English et al., 1997), and occurs downstream of the point where the Slave River fans into distributaries.

Climate in the SRD is strongly seasonal, with cold winters (mean January temperature = -23.1°C) and cool summers (mean July temperature = 15.9°C) (Environment Canada, 2002). The SRD receives approximately 320 mm of precipitation annually, half of which falls as rain during the thaw season. Average thaw season temperature and relative humidity, flux-weighted based on potential evapotranspiration (Malmstrom, 1969; Dingman, 1993), are 11.4°C and 69.2%, respectively, using 1971–2000 normals measured at Hay River, NWT, located 150 km west of the SRD (Environment Canada, 2002).

The Slave River begins its 420 km course north to Great Slave Lake at the confluence of the Peace River and Rivière des Rochers, at the northern edge of the Peace-Athabasca Delta in northern Alberta (Fig. 1). The Slave River receives ~66% of its annual flow from the Peace River (English et al., 1996), with the remaining flow mainly supplied by Lake Athabasca and the Athabasca River via the Rivière des Rochers, as well as other northward-flowing tributaries upstream of the Peace-Rochers confluence. The Slave River drains 15,100 km^2 (Prowse et al., 2002), and its discharge contributes 74% of all inflow to Great Slave Lake (Gibson et al., 2006b), the primary source of water for the Mackenzie River. Additional water sources for Great Slave Lake are its bordering catchments, contributing 21% of the lake's inputs, and direct precipitation, contributing 5%, based on water budget modeling (Gibson et al., 2006b).

Wind-forced seiche events from Great Slave Lake can inundate the delta front and affect water levels in the Slave River and outer delta lakes (Gardner et al., 2006). Southwest winds force the majority of seiche set-up events, predominantly in the late summer and early autumn when the hydraulic resistance of the Slave River is low. The majority of seiche events are low in magnitude, with water level increases of 0.05–0.09 m. Levee heights along the lower distributaries of the Slave River are in the range of most seiche events, resulting in the potential for flooding along the delta front.

English et al. (1997) identified three distinct biogeographical zones in the active part of the SRD: the outer, youngest portion of the delta, which supports aquatic and emergent vegetation and where lakes are susceptible to annual floods during the spring freshet due to low levee heights, at or within 0.1 m of low summer Great Slave Lake levels; the oldest apex portion of the delta, where levee heights are 2.5–3 m above low summer Great Slave Lake water levels, flooding is infrequent, and climax forest communities of white spruce (*Picea glauca*) dominate; and the mid-delta zone, an ecological transition zone between the outer and apex portions of the delta, where alder-willow vegetation complexes dominate, levee heights are 0.5–2.5 m above low summer Great Slave Lake water levels, and widespread flooding is thought to occur every five to seven years (Prowse et al., 2002). Lakes from each of these delta zones have been selected for this study. Maximum lake depths range between 0.15 and 4 m, with the exception of SD30 (Ring Lake, a partially cutoff meander of the Slave River), which has a maximum depth of 10 m.

Methodology

Forty lakes spanning all three biogeographical zones in the SRD and extending well upstream, plus Great Slave Lake, SD30 (Ring Lake), and the Slave River, were sampled with the aid of a helicopter between 22 and 24 September 2002, and on 23 May 2003, 23 June 2003, 25 July 2003, and 15 August 2003 (Fig. 1). A subset of six lakes was also sampled on 03 September 2003. Water samples were collected from ~10 cm below the water surface at the center of each study lake in 30 mL high density polyethylene bottles and sealed tightly before transportation to the University of Waterloo Environmental Isotope Laboratory. The $^{18}O/^{16}O$ and $^{2}H/^{1}H$ ratios were measured using standard methods (Epstein and Mayeda, 1953; Coleman et al., 1982). Results are reported as δ values, representing deviations in per mil (‰) from the V-SMOW standard, such that $\delta^{18}O_{sample}$ or $\delta^{2}H_{sample} = 10^3[(R_{sample}/R_{V\text{-}SMOW}) - 1]$ where R is the ratio of $^{18}O/^{16}O$ or $^{2}H/^{1}H$ in sample and standard, normalized to $\delta^{18}O$ and $\delta^{2}H$ values for Standard Light Antarctic Precipitation of −55.5‰ and −428‰ (Coplen, 1996). Analytical uncertainties for $\delta^{18}O$ and $\delta^{2}H$ are ±0.2‰ and ±2‰, respectively, based on replicate field samples.

Total inorganic suspended sediment (TSS) analysis was also conducted on water samples collected during the 23 May 2003 sampling campaign. A known volume of water was agitated and filtered through a 1.2 µm glass microfiber filter of a known weight. Filters were ashed at 550°C for four hours and reweighed to determine the mineral matter content of the filtered sample (Dean, 1974). TSS results are reported in g L^{-1}. Analytical uncertainty for TSS is ±0.002 g L^{-1}, based on replicate field samples.

Meteorological data for 2003 were obtained for Hay River, NWT (Environment Canada, 2004; Fig. 1). The isotopic composition of amount-weighted mean annual (1962–1965) precipitation (δ_P) was obtained from Fort Smith, NWT (Birks et al., 2004). The isotopic composition of evaporation flux-weighted thaw season precipitation (δ_{PS}) is taken from Gibson and Edwards (2002). The reported isotopic composition of snow (δ_{snow}) is given as a range, based on snow samples collected from lakes SD2, 15, 20, 28, 29, 33, and 39 during an early May 2004 field campaign, prior to ice breakup.

Total precipitation amounts reported were measured at Environment Canada's Hay River, NWT, meteorological station. Snowfall was converted to snow-water equivalent and summed with total rainfall.

Results and Interpretation

AN ISOTOPIC FRAMEWORK FOR EVALUATING LAKEWATER BALANCES

Natural isotope labeling of precipitation is typically manifested by the existence of prominent trends in $\delta^{18}O$-$\delta^{2}H$ space, reflecting systematic mass-dependent partitioning of water molecules in the hydrologic cycle (Edwards et al., 2004). The isotopic composition of precipitation at a site generally clusters along a Local Meteoric Water Line (LMWL) lying near the Global Meteoric Water Line (GMWL) of Craig (1961). The GMWL, given by $\delta^2H = 8\delta^{18}O + 10$, closely describes the observed relationship between $\delta^{18}O$ and $\delta^{2}H$ for amount-weighted annual precipitation worldwide. Based on analysis of weighted monthly precipitation collected at Fort Smith (1962–1965), the LMWL for the SRD can be approximated by $\delta^2H = 6.7\delta^{18}O - 19.2$ (Birks et al., 2004). Local surface waters that have undergone subsequent evaporation are offset from the LMWL in proportion to their individual water balances, often forming a variably well-defined linear trend (Local Evaporation Line or LEL) having a slope in the range 4–6.

The LEL can also be predicted using the linear resistance model of Craig and Gordon (1965), which accounts for ^{18}O and ^{2}H buildup in evaporating water bodies, by incorporating appropriate local isotopic and hydroclimatic information (Barnes and Allison, 1983; Gibson and Edwards, 2002; Edwards et al., 2004; Wolfe et al., 2007b). These include the respective $\delta^{18}O$ and $\delta^{2}H$ values of local precipitation and ambient atmospheric moisture, as well as relative humidity and air temperature prevailing during the open-water season. Key reference points along the LEL include the steady-state isotopic composition for a terminal basin (δ_{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 isotopic composition (δ^*), which indicates the maximum potential transient isotopic enrichment of a lake as it approaches complete desiccation (see Appendix).

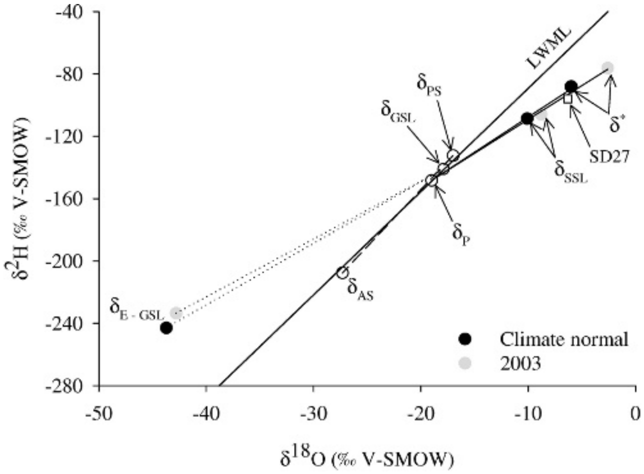

FIGURE 2. Samples collected on 25 July 2003 from Great Slave Lake (δ_{GSL}, the most isotopically depleted lake at the time of sample collection) and SD27 (the most isotopically enriched lake at the time of sample collection) superimposed on the climate normal and 2003 isotopic frameworks, showing the isotopic composition of amount-weighted mean annual (1962–1965) precipitation (δ_P) from Fort Smith, NWT (Birks et al., 2004), the isotopic compositions of evaporation-flux-weighted thaw season precipitation (δ_{PS}; Gibson and Edwards, 2002) and atmospheric moisture (δ_{AS}), the steady state isotopic composition of a terminal basin (δ_{SSL}), the limiting isotopic composition (δ*), and the isotopic composition of Great Slave Lake vapor (δ_{E-GSL}).

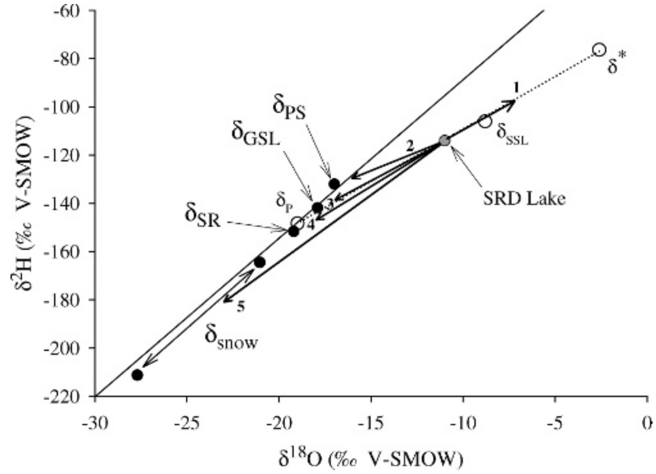

FIGURE 3. Potential isotopic trajectories of a theoretical Slave River Delta (SRD) lake in response to (1) evaporation, (2) thaw season precipitation (δ_{PS}; Gibson and Edwards, 2002), (3) Great Slave Lake (δ_{GSL}) exchange, (4) Slave River (δ_{SR}) flooding, and (5) snowmelt (δ_{snow}) input, superimposed on the 2003 isotopic framework (see Fig. 2). Isotopic framework parameters are shown as open circles. In this example, the theoretical lake is shown to plot on the Local Evaporation Line (LEL), indicating the lake is fed by water of isotopic composition similar to mean annual precipitation.

As shown in Figure 2, the isotopic framework for the SRD includes two alternative LELs to aid in the evaluation of the isotopic evolution of lakewaters during summer 2003. Both LELs are anchored by the estimated amount-weighted mean annual isotopic composition of precipitation (δ_P) and assume the isotopic composition of ambient atmospheric moisture (δ_{AS}) is in approximate isotopic equilibrium with evaporation-flux-weighted summer precipitation (δ_{PS}; see Gibson and Edwards, 2002). The predicted LEL prevailing under average thaw-season conditions, based on 1971–2000 climate normals measured at Hay River, is described by $\delta^2H = 4.5\delta^{18}O - 63.5$, whereas the predicted LEL for the 2003 thaw season ($\delta^2H = 4.1\delta^{18}O - 69.7$) has a slightly lower slope and more enriched δ_{SSL} and δ* values because of lower-than-normal relative humidity and higher-than-normal temperature (Table 1).

Although the predicted "climate normal" LEL is probably a good indicator of average thaw-season conditions in the SRD, it is clear from the behavior of several lakes in 2003 that the season-specific LEL provides a more appropriate metric for assessing the isotope hydroclimatology of this particular season. For example, in mid-summer, SD27 is one of a cluster of lakes that plot close to the climate normal δ* (Fig. 2), but was not near desiccation when observed in the field. This deviation from the climate normal isotopic framework suggests that SD27, and all other SRD study lakes, evolved isotopically under hydrometeorological conditions that differed from climate normals.

TABLE 1

Isotopic framework parameters are derived using flux-weighted thaw season climate data from Hay River (Environment Canada, 2002, 2004) and Equations 6, 7, 9 and 10 in the Appendix.

	Climate normal	2003
$\delta^{18}O_{SSL}$, δ^2H_{SSL} (‰)	−10.1, −109	−8.8, −106
$\delta^{18}O$*, δ^2H* (‰)	−6.0, −88	−2.6, −76
$\delta^{18}O_{E-GSL}$, δ^2H_{E-GSL} (‰)	−43.7, −243	−42.8, −234
LEL	4.5 $\delta^{18}O$ – 63.5	4.1 $\delta^{18}O$ – 69.7
h (%)	69.2	62.8
T (°C)	11.4	13.4

As expected, the isotopic composition of Great Slave Lake ($\delta^{18}O$, δ^2H = −17.9‰, −142‰) lies close to the reported δ_P value from Fort Smith (Fig. 2). Because Great Slave Lake is a large, deep lake (surface area = 28,400 km^2, maximum depth = 614 m) (CNCIHD, 1978) with a long residence time, it is probable that its isotopic composition will closely approximate the regional composition of long-term average precipitation and river inputs. Figure 2 also identifies predicted vapor forming from Great Slave Lake (δ_{E-GSL}), which has a distinct depleted isotopic signature and represents a potential source of atmospheric moisture for the SRD.

HYDROLOGICAL PROCESSES IN THE SLAVE RIVER DELTA

The major sources of water for SRD lakes—the Slave River, Great Slave Lake (via seiche events), snowmelt, and summer precipitation—each possess characteristic isotopic signatures (Fig. 3). This key feature, along with the enrichment effects of evaporation, can be used to identify the hydrological processes that drive changes in SRD lakewater isotope compositions. The relative roles of these hydrological processes on SRD lakes during the 2003 thaw season are described below in the context of expected isotopic trajectories (Fig. 3). As Figure 3 illustrates, a lake's position relative to the reference LEL will vary depending on the relative importance of the various input sources and evaporation.

Flooding and Snowmelt

Lakewater samples were collected from SRD lakes on 23 May 2003 to evaluate the role of river flooding and snowmelt. Prior to sampling, daily average temperature exceeded 0°C on 15 days in May (Environment Canada, 2004) and the Slave River at Fitzgerald, Alberta, had been ice-free for approximately 11 days (Water Survey of Canada, 2006). These data suggest that the majority of snow- and ice-melt in the SRD occurred within two weeks of sample collection, and minimal isotopic evaporative enrichment of delta lakes took place prior to sampling. Instead, strong flooding and snowmelt signals are evident in several lakes in the 23 May 2003 sample set (Fig. 4a). The $\delta^{18}O$-$\delta^{2}H$ plot of this data set clearly shows two clusters of samples: those that were strongly influenced by river flooding, and those that only received catchment-sourced snowmelt. Flooded sites are more isotopically depleted than non-flooded sites, and cluster around the Slave River isotopic composition ($\delta^{18}O$, $\delta^{2}H$ = −19.2‰, −152‰), with $\delta^{18}O$ and $\delta^{2}H$ values ranging between −19.2‰ and −17.1‰ and −155‰ and −146‰, respectively. In contrast, non-flooded sites are more isotopically enriched than flooded sites and are less strongly clustered ($\delta^{18}O$ and $\delta^{2}H$ = −16.2‰ and −139‰ to −10.6‰ and −122‰), suggesting snowmelt influences on individual lakes were variable. Total inorganic suspended sediment (TSS) data support the interpretation of isotopically distinct flooded and non-flooded lakes. Flooded lakes with lower $\delta^{18}O$ signatures contain higher concentrations of TSS, delivered by Slave River floodwaters, compared to non-flooded lakes with higher $\delta^{18}O$ values (Fig. 5). Slave River sediment is also discharged in high quantities into Great Slave Lake during the spring melt, resulting in the elevated TSS concentration measured in the nearshore region of Great Slave Lake (TSS = 0.016 g L^{-1}).

While river flooding clearly influences early-season isotopic signatures in several SRD lakes, the impact of snowmelt (δ_{snow}) can also be observed in lakewater isotopic compositions. Three SRD lakes (SD2, SD10, and SD38), which all received early spring floodwaters, are equally or more depleted than Slave River water (Fig. 4a). For example, the $\delta^{18}O$ ($\delta^{2}H$) values of SD2 and the Slave River are −19.2‰ (−155‰) and −19.2‰ (−152‰), respectively. While it is clear from TSS data that SD2 did receive Slave River floodwater (SD2 TSS = 0.1 g L^{-1}; Fig. 5), the lake's depleted isotopic signature indicates it was also influenced to a lesser degree by snowmelt ($\delta^{18}O$ and $\delta^{2}H$ range of snow = −21.1‰ to −27.7‰ and −165‰ to −211‰).

Snowmelt influence is also evident in lakes that are more isotopically enriched than Slave River water. For example, lakes that did not receive Slave River floodwater were drawn below the predicted LEL toward the isotopic composition of snow. Even the most isotopically enriched lakes sampled on 23 May 2003 (SD12, SD33, and SD35) were influenced by snowmelt. During a September 2002 reconnaissance sampling campaign,

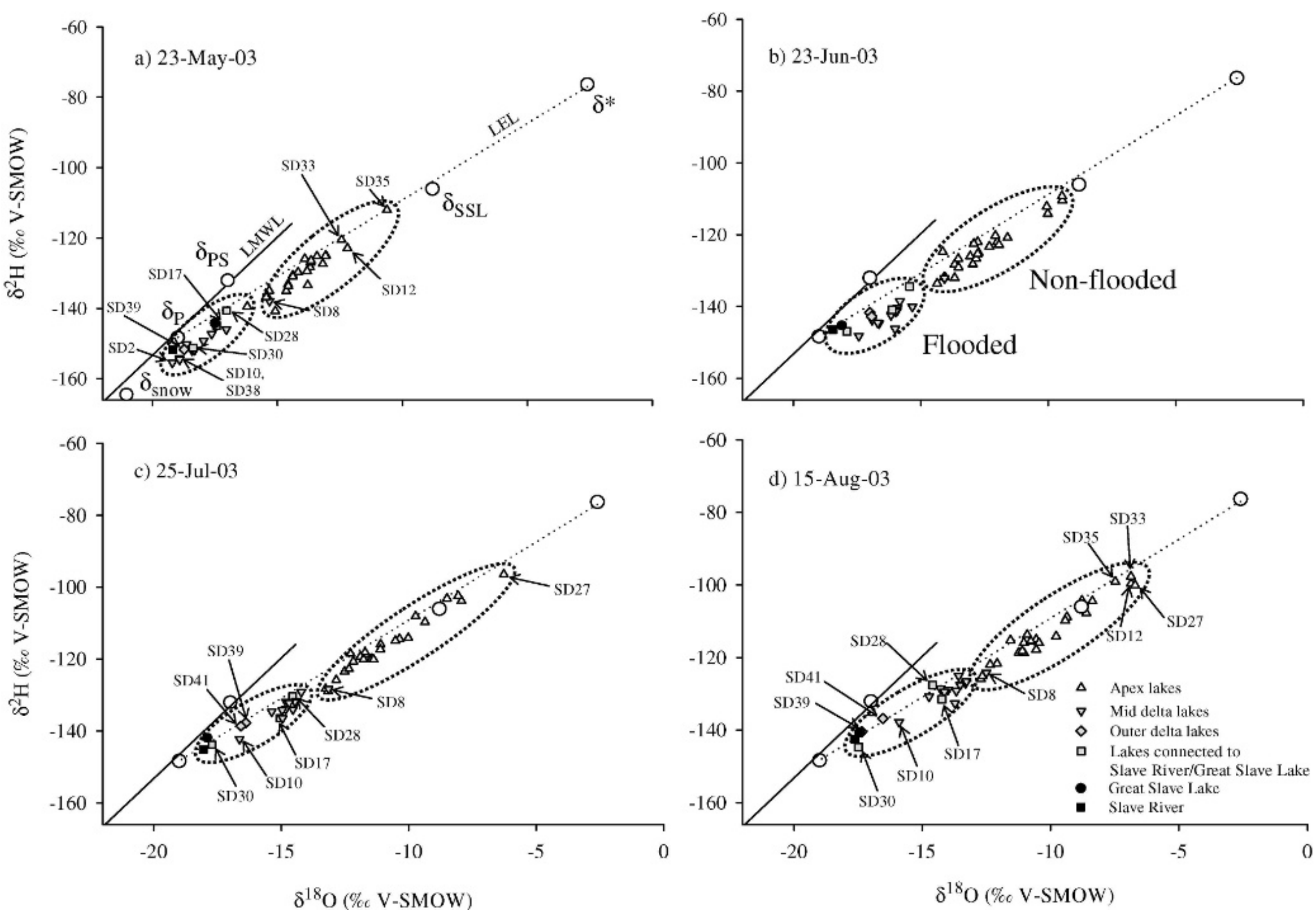

FIGURE 4. Results of SRD regional sampling campaigns conducted on (a) 23 May 2003, (b) 23 June 2003, (c) 25 July 2003, and (d) 15 August 2003. The isotopic compositions of all SRD lakes sampled are superimposed on the 2003 climate isotopic framework (see Fig. 2). Lakes identified by name in the text are labeled. Flooded and non-flooded clusters of lakes are circled with a dashed line, and are labeled in (b). Isotopic framework parameters are shown as open circles.

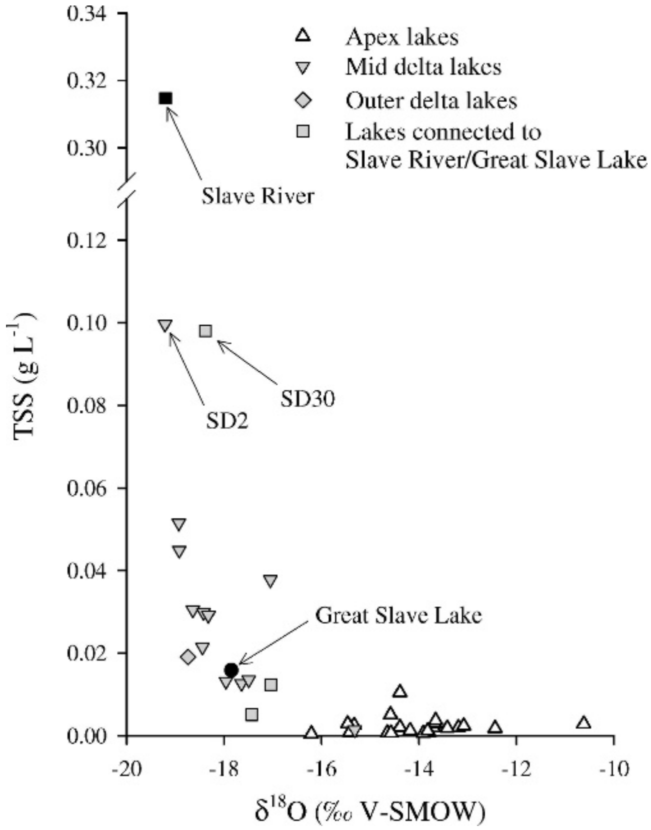

FIGURE 5. Total inorganic suspended sediment (TSS), expressed in g L^{-1}, in SRD lakes from water samples collected on 23 May 2003. Lakes that have high TSS concentrations were flooded by the Slave River during the spring thaw, while lakes that were not flooded by the Slave River have low TSS concentrations.

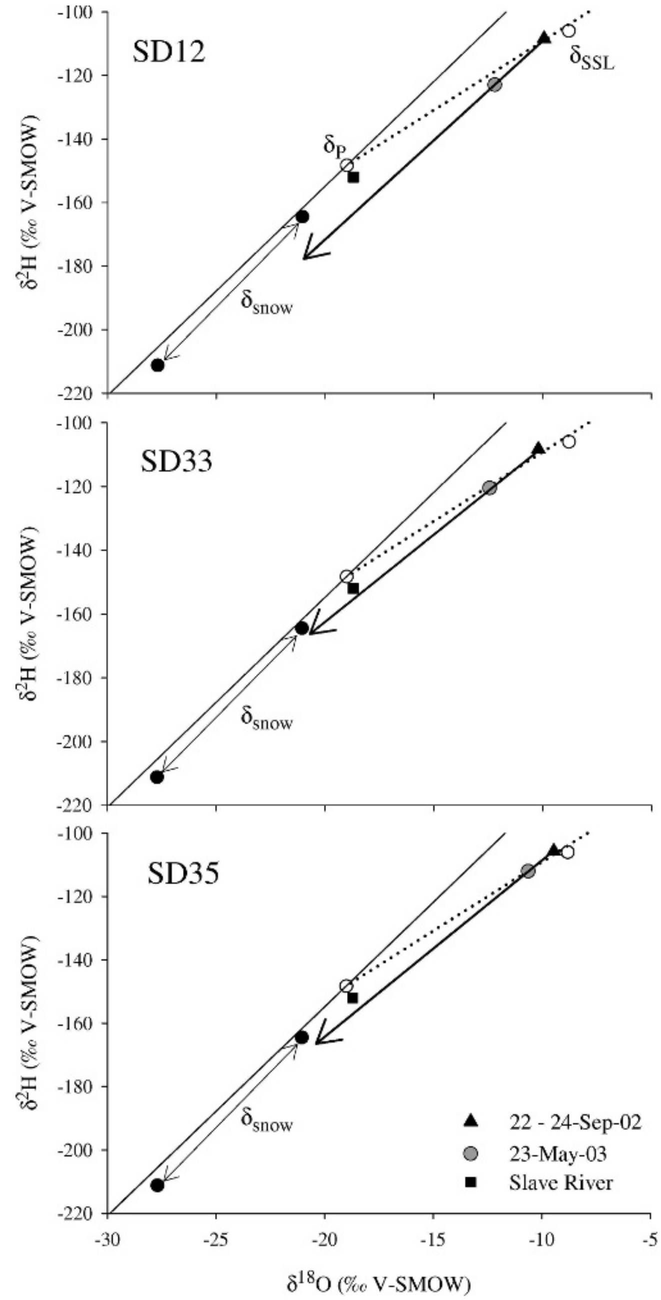

FIGURE 6. Depletion trajectories of non-flooded lakes SD12, SD33, and SD35 between September 2002 and May 2003 are toward the isotopic composition of snow (δ_{snow}), in response to an influx of catchment-sourced snowmelt during spring melt period. Isotopic compositions are superimposed on the 2003 climate isotopic framework (see Fig. 2). Isotopic framework parameters are shown as open circles.

those three lakes had the highest isotopic compositions, with δ^{18}O (δ^{2}H) values of −9.9‰ (−108‰), −10.2‰ (−108‰), and −9.4‰ (−106‰), respectively. On 23 May 2003, the δ^{18}O (δ^{2}H) values of the same three lakes were lowered to −12.2‰ (−123‰), −12.4‰ (−121‰), and −10.6‰ (−112‰), respectively. Plotting of these results in δ^{18}O-δ^{2}H space reveals that the trajectory of isotopic depletion between September 2002 and May 2003 was toward the isotopic composition of snow (Fig. 6; see also Fig. 3).

The magnitude of river floodwater and snowmelt dilution on May lakewater balances can be estimated using a two-component mixing model incorporating end-of-thaw-season lakewater isotopic composition from 2002, early thaw-season lakewater isotopic composition from 2003 (Fig. 4a), Slave River or snowmelt isotopic composition (Fig. 4a), and identification of basins that received river water (Figs. 4a, 5). For example, river floodwater dilution of SD1 (Fig. 7a) was determined by:

$$\%\text{ floodwater dilution} = \left[\left(\delta_{\text{SD1 May 2003}} - \delta_{\text{SD1 Sept 2002}}\right) / \left(\delta_{\text{Slave River May 2003}} - \delta_{\text{SD1 Sept 2002}}\right)\right] \times 100 \quad (1)$$

Similar calculations were performed for lakes that only received snowmelt, such as SD 11 (Fig. 7b):

$$\%\text{ snowmelt dilution} = \left[\left(\delta_{\text{SD11 May 2003}} - \delta_{\text{SD11 Sept 2002}}\right) / \left(\delta_{\text{snow}} - \delta_{\text{SD11 Sept 2002}}\right)\right] \times 100 \quad (2)$$

Calculations were performed for both δ^{18}O and δ^{2}H and average percent dilution values were obtained for each basin. These first-order mass-balance calculations indicate that the flooded basins were diluted from ~70% to as much as 100% by river water. While these estimates do not account for changes in volume nor the added effect of snowmelt input, spatial interpolation suggests that flooding occurred adjacent to the main distributary channels of the Slave River in the active mid- and outer delta zones, with the exception of SD8 (Willow Lake) (Fig. 8a). The spatial distribution of floodwater, estimated by the 70% dilution contour, is consistent with field observations and elevated TSS concentrations in lakes situated in the active delta. In this part of the delta, natural levee heights are 0.1–1.5 m above

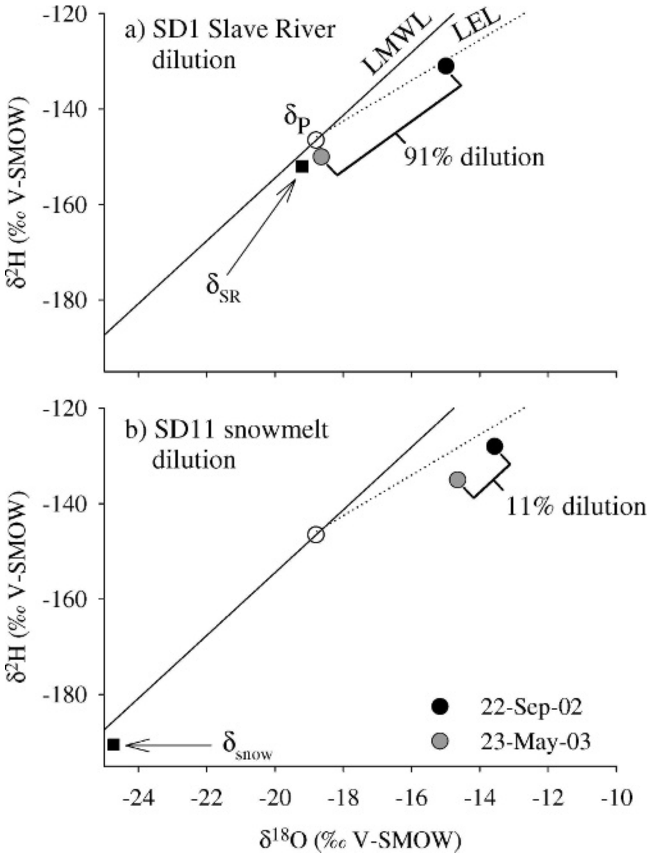

FIGURE 7. Examples showing dilution percentage estimates for (a) SD1, an apex lake flooded by the Slave River (δ_{SR}) in May 2003, and (b) SD11, a lake in the apex zone of the delta that received exclusively snowmelt input (δ_{snow}) during the spring melt. Snowmelt dilution is calculated using an average snowmelt value (δ^{18}O, δ^2H = −24.7‰, −191‰). Isotopic compositions are superimposed on the 2003 climate isotopic framework (see Fig. 2).

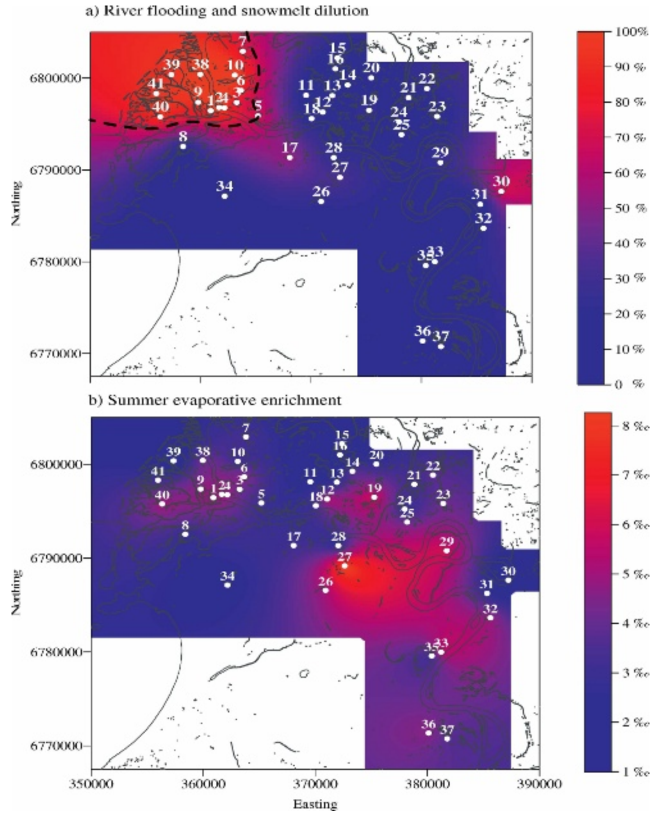

FIGURE 8. The spatial extent of (a) river flooding and snowmelt dilution and (b) summer evaporative enrichment in lakes in 2003 interpolated using data from Figure 4. In (a), two-component mixing indicates that flooding occurred in areas adjacent to the main distributary channels of the Slave River in the mid- and outer portions of the active delta (mapped as red areas). Elsewhere, lakes received exclusively snowmelt in the spring (mapped as mainly blue areas). The observed spatial extent of flooding corresponds with the 70% dilution contour, shown as a black contour. Summer isotopic enrichment in (b) represents enrichment in ^{18}O (‰) between 23 May 2003 and 15 August 2003.

Great Slave Lake water levels (English et al., 1997), and lakes are susceptible to inundation by Slave River floodwaters. Snowmelt dilutions of between ~7 and 35% were calculated for non-flooded sites, located in the older part of the delta where bank levees are greater than 2.5 m in relief (English et al., 1997).

Evaporation

By mid-summer (Fig. 4c), evaporative isotopic enrichment of every lake as well as the Slave River had occurred. The dominant effect of evaporation was also expressed by increased clustering of lakes along the LEL in the absence of dilution from summer precipitation (Figs. 4b–4d; see also Fig. 3). In fact, seven lakes are shown to exceed δ_{SSL} by 15 August 2003 indicating non-steady state evaporation (Fig. 4d), consistent with field observations of lake level drawdown. The four most isotopically enriched lakes, SD12, SD27, SD33, and SD35, were among the shallowest of apex lakes and were not affected by spring flooding.

Increases in lakewater δ^{18}O between May and August range from 0.9‰ to 8.4‰ (δ^2H = 5‰ to 41‰) (Fig. 8b). The greatest isotopic enrichment occurred in lakes in the apex zone of the delta that lack channel connections to the Slave River and were not affected by spring flooding. In contrast, minimal isotopic enrichment is evident in lakes with direct connections to the Slave River or Great Slave Lake, and in those lakes that were inundated by Slave River floodwaters during the spring melt (Fig. 8a).

In both the June and July data sets, lakes continue to be separated in δ^{18}O-δ^2H space, depending on whether they were flooded by the Slave River in the spring (Figs. 4b, 4c). Lakes that did not receive Slave River floodwater continue to be more isotopically enriched due to evaporation compared to lakes that were flooded (although some non-flooded lakes still plot below the LEL, reflecting strong early season snowmelt signals). Direct connections between the Slave River or Great Slave Lake also limit possible evaporative enrichment in delta lakes. For example, in June, July, and August, six lakes capable of exchanging water with the Slave River or Great Slave Lake (SD10, SD17, SD28, SD30, SD39, and SD41) generally have lower isotopic signatures than unconnected lakes. The influence of both connectivity and thaw season precipitation on delta lakes will be discussed in more detail in the following sections.

Great Slave Lake-Slave River Exchange

Of the six of the lakes sampled in the SRD that can readily exchange water with the Slave River or Great Slave Lake, SD10, SD17, SD28, and SD30 have direct channel connections to the Slave River. SD39 and SD41 are situated on the outer delta, where dominant emergent and aquatic vegetation communities and low levee heights, at or within 0.1 m of low summer Great Slave Lake levels (English et al., 1997), allow mixing of lakewater with that of Great Slave Lake, particularly during high spring water levels and late summer seiche events. All of the six connected lakes behave differently isotopically compared with other delta lakes, reflecting the effects of Slave River or Great Slave Lake exchange on their water budgets.

Spring flooding was mainly concentrated in the mid- and outer delta (Fig. 8a). Samples from 23 May 2003 show that connected lakes in this area of the delta (SD10, $\delta^{18}O$ and δ^2H = −18.9‰ and −154‰; SD39, $\delta^{18}O$ and δ^2H = −18.7‰ and −152‰) are isotopically similar to the Slave River ($\delta^{18}O$ and δ^2H = −19.2‰ and −152‰) and Great Slave Lake ($\delta^{18}O$ and δ^2H = −17.5‰ and −144‰) (Fig. 4a). SD41, a third connected lake in the active delta, was submerged under Great Slave Lake during the spring of 2003 and no water sample was collected. Its isotopic signature is assumed to be identical to that of Great Slave Lake. SD30 (Ring Lake), a partially cutoff meander of the Slave River located in the apex zone of the delta, is isotopically similar to outer delta lakes, with an isotopic signature of −18.4‰ for $\delta^{18}O$ and −151‰ for δ^2H. The persistent channel connection between SD30 and the Slave River allows ample mixing between the two. SD17 and SD28 are also both situated in the apex zone of the SRD, but have longer, narrower channel connections to the Slave River than SD30. Despite their channel connections, these two lakes are more isotopically enriched than the Slave River during the spring melt, with $\delta^{18}O$ and δ^2H values of −17.4‰ and −145‰ and −17.0‰ and −141‰, respectively. The isotopic signatures of SD17 and SD28 indicate that penetration by Slave River floodwater was less significant than in other connected lakes, a likely consequence of both the length and depth of the connecting channel and the spatial distribution of flooding.

Later in the thaw season, evaporative isotopic enrichment is severely suppressed in lakes capable of exchange with Slave River or Great Slave Lake water (Fig. 4c). On 25 July 2003, the Slave River had a $\delta^{18}O$ (δ^2H) value of −18.1‰ (−145‰), while that of SD30 was −17.7‰ (−144‰). SD30 maintains its channel connection with the Slave River throughout the thaw season and receives a continual input of Slave River water. SD10, SD39, and SD41, lakes in the active delta with very low isotopic signatures during the spring thaw, continue to be more isotopically depleted than all other lakes ($\delta^{18}O$ and δ^2H = −16.6‰ and −142‰, −16.4‰ and −138‰, and −16.6‰ and −139‰, respectively), indicating periodic input of isotopically depleted Slave River or Great Slave Lake water, possibly through seiche events during the summer. On 25 July 2003, apex lakes SD17 and SD28 have $\delta^{18}O$ (δ^2H) values of −15.1‰ (−136‰) and −14.6‰ (−130‰), similar to non-connected, flooded lakes in the outer delta (Fig. 4c). The isotopic compositions of SD17 and SD28 indicate inputs of Slave River water have been restricted since the spring flood, possibly by declining water levels in the Slave River following the flood peak. Field observations also indicate that emergent vegetation was growing in the channels of SD17 and SD28 at the time of sampling, further impeding Slave River inflow. Consequently, while these lakes continue to be more isotopically depleted than nearby, unconnected apex zone lakes, SD17 and SD28 undergo more evaporative enrichment than other connected lakes in the SRD.

By 15 August 2003, a strong distinction exists between lakes that have a direct connection with the Slave River or Great Slave Lake and those that do not (Fig. 4d). Outer delta lakes SD39 and SD41 are among the most isotopically depleted water bodies sampled, with $\delta^{18}O$ (δ^2H) values of −17.4‰ (−140‰) and −16.5‰ (−137‰), respectively. It is probable that seiche events, which occur most frequently during the late summer and early autumn (Gardner et al., 2006), facilitate water exchange between Great Slave Lake ($\delta^{18}O$ and δ^2H = −17.4‰ and −141‰) and SD39 and SD41. SD30 and SD10 also continue to receive river water during the late summer. Because of its river connection, SD30 maintains low $\delta^{18}O$ (δ^2H) values of −17.5‰ (−145‰), similar to those of the Slave River ($\delta^{18}O$ and δ^2H = −17.6‰ and −142‰). SD10 ($\delta^{18}O$ and δ^2H = −15.9‰ and −138‰) has a narrower direct connection to a major distributary channel in the active delta, limiting its evaporative enrichment. Because of their open hydrologic status, evaporative isotopic enrichment in SD10, SD30, SD39, and SD41 has been minimal. Consequently, these lakes are separated in $\delta^{18}O$-δ^2H space from lakes that are not directly connected to the distributary channel network and for which evaporative enrichment over the course of the thaw season is significant. SD17 and SD28 continue to undergo evaporative enrichment as restrictions in channel connections persist and limit the influence of Slave River inflow on the water balances of these two lakes. As a result, their isotopic signatures ($\delta^{18}O$ and δ^2H = −14.2‰ and −131‰ and −14.6‰ and −128‰, respectively) are similar to those of the most isotopically depleted, non-connected, flooded lakes in the active outer and mid-delta (Fig. 4d).

Thaw Season Precipitation

The regional sampling campaigns carried out in the SRD offer no strong evidence of lakewater isotopic depletion due to thaw season precipitation, in the form of the expected trajectory of a delta lake toward summer precipitation composition (δ_{PS}; Fig. 3). This observation is consistent with below-normal precipitation during the first three months of the thaw season (Fig. 9) and 15 August 2003 results, which indicate that all lakes incapable of exchanging water with the Slave River or Great Slave Lake were more isotopically enriched than δ_{PS} ($\delta^{18}O$, δ^2H = −17.0‰, −132‰; see Fig. 3). While precipitation during the month of August exceeded climate normal conditions, the majority of August rain fell after the 15 August 2003 sampling campaign (59.6 mm).

However, the results of samples collected from four lakes (SD2, SD15, SD29, and SD33) after 15 August 2003 illustrate the isotopic responses of delta lakes to thaw season precipitation. Sampling conducted between May and August demonstrates that these four lakes became progressively more evaporatively enriched over the course of the summer. Samples collected on 03 September 2003, however, show a strong reduction in lakewater isotopic signatures in response to late season precipitation (Fig. 10). Precipitation-induced isotopic depletion at SD2, SD15, SD29, and SD33 between 15 August 2003 and 03 September 2003 ranges from −2.5‰ to −9.8‰ for $\delta^{18}O$ and −9‰ to −40‰ for δ^2H.

Between 15 August 2003 and 03 September 2003, 39 mm of rain were recorded at Hay River (Environment Canada, 2002), although an unusual snow event was reported by residents of Fort Resolution on 01 September 2003. A lake effect storm, with precipitation derived from Great Slave Lake vapor (δ_{E-GSL}; see Fig. 2), would produce snow that is more isotopically depleted than typical SRD summer precipitation (δ_{PS}; $\delta^{18}O$, δ^2H = −17.0‰, −132‰). For example, snow sampled during a lake effect storm in the SRD in September 2002 had an isotopic composition that plotted above the LMWL (Fig. 10). Because SD15 is a relatively deep (~4 m), sinuous lake, a sample collected from the margin of the lake could reflect the isotopic composition of the storm's snow, rather than the average isotopic composition of the lake itself. Such a storm would be capable of producing the depletion trajectories observed in the other three sampled lakes (Fig. 10). Assuming the lakewater sample from SD15 reflects the isotopic composition of the storm's precipitation, it is possible to estimate the maximum amount of storm-sourced water in each

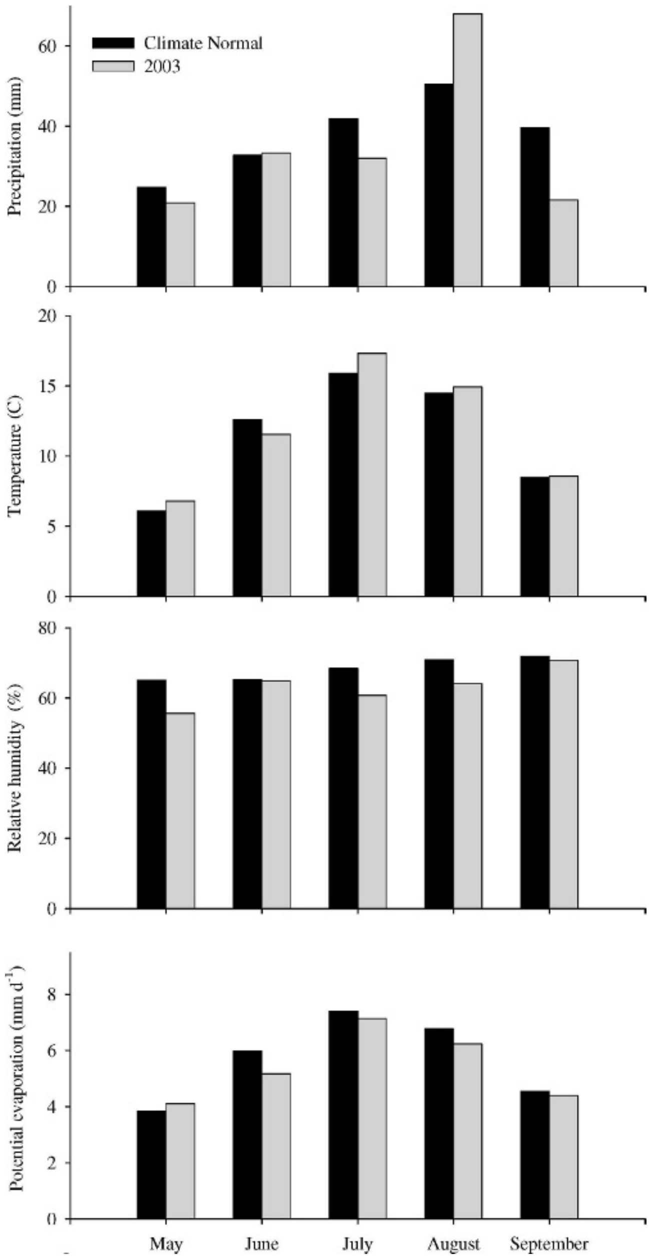

FIGURE 9. Monthly distribution of total thaw season precipitation, average temperature and average relative humidity and potential evaporation for 2003 in comparison to climate normal values (1971–2000) for Hay River, NWT (Environment Canada, 2002).

lake at the time of sampling. For example, at SD33, up to 20% of the lake may have been made up of precipitation from the storm at the time of sampling, encompassing both precipitation falling directly on the lake and runoff from the catchment. At SD29, snowfall may have made up 10% of the lake's water at the time of sampling. Comparably, isotopic depletion at shallow SD33 (δ^{18}O, δ^{2}H = −16.7‰, −138‰) is more significant than that of deeper SD29 (δ^{18}O, δ^{2}H = −11.2‰, −118‰). A wide grass fringe may have captured some of the catchment-sourced runoff at SD29 and prevented it from mixing completely with lakewater. In contrast, a terrestrial meadow surrounding SD33 may have promoted runoff into the lake, where no emergent vegetation fringe prevented mixing between runoff and lakewater. At SD2, Slave River influences may have contributed to the lake's late season water balance and drawn the isotopic composition of that lake below the LEL. While the degree of depletion in response to this late season precipitation varies between lakes and is related to lake surface area and volume, catchment characteristics, and likely also spatial variations in the intensity, duration, and isotopic composition of rainfall and snowfall, their isotopic responses are comparable. As these lakes span both the mid-delta and apex zones of the SRD, it is likely that other unconnected lakes across the delta responded isotopically in a similar manner.

Discussion

The isotopic evolution of lakes in the SRD has been evaluated against an isotopic framework based on flux-weighted climate data from the 2003 thaw season. The isotopic framework used in this study is based on climate data specific to the year of sampling, thus the hydroclimatic conditions under which lakes evolved are inherently included in the framework. In 2003, average thaw season temperature and relative humidity differed from climate normals, particularly during the months of July and August when potential evaporation is greatest (Fig. 9). The results of these deviations were a decrease of 6.4% in flux-weighted relative humidity and an increase of 2°C in flux-weighted temperature during the thaw season as compared to climate normal conditions. Accordingly, δ_{SSL} and δ^* values were higher in δ^{18}O by 1.5‰ (δ^{2}H = 5‰) and 3.6‰ (δ^{2}H = 14‰) compared to calculations using climate normal values (Table 1). Consequently, in 2003 SRD lakes had the potential to become more isotopically enriched than they would under climate normal conditions. Assuming climate normal conditions appropriately represent the hydroclimatic conditions under which a lake evolves over the course of a thaw season may thus under- or over-estimate potential evaporative enrichment and result in the calculation of inappropriate δ_{SSL} and δ^* values. In this case, using a year-specific isotopic framework significantly improves semi-quantitative assessments of lakewater balance conditions. The 2003-specific framework is strongly supported by the isotopic compositions of Great Slave Lake and the most isotopically enriched lakewater sample (SD27; Fig. 2). The tight clustering of mid-summer lakewater isotopic compositions along the predicted LEL, when thaw season precipitation was minimal, provides further support for the framework, including the estimated value for δ_{AS} (Figs. 4c, 4d, 10).

Using an isotopic framework based on summer 2003 climate data, evaluations of SRD lakewater isotopic compositions during the 2003 thaw season reveal that the relative influence of hydrological processes in the delta varied spatially and over time. River flooding during the spring ice breakup was the dominant input into mid- and outer delta lakes, while apex lakes were not affected by spring flooding. In contrast, catchment-sourced snowmelt affected all delta lakes. While snowmelt input varied with lake catchment size and presumably with spatial variations in snowpack depth and density, it was the dominant input to apex lakes during the spring. Snowmelt input played a less important role in lakes affected by river flooding, probably because a greater volume of floodwater versus snowmelt entered each flooded lake.

As the thaw season progressed, evaporation became the dominant factor controlling lakewater isotopic signatures across the delta. However, the degree of evaporative enrichment in SRD lakes varied. Evaporative enrichment was greater in lakes that were not flooded by the Slave River during the spring melt compared to lakes that were. Lakes capable of exchange with the Slave River or Great Slave Lake were minimally affected by evaporation. Evaporative enrichment following ice breakup was therefore partially controlled by the nature and spatial distribution of spring flooding, the degree of snowmelt influence on each lake, and the strength of connections with the distributary channel

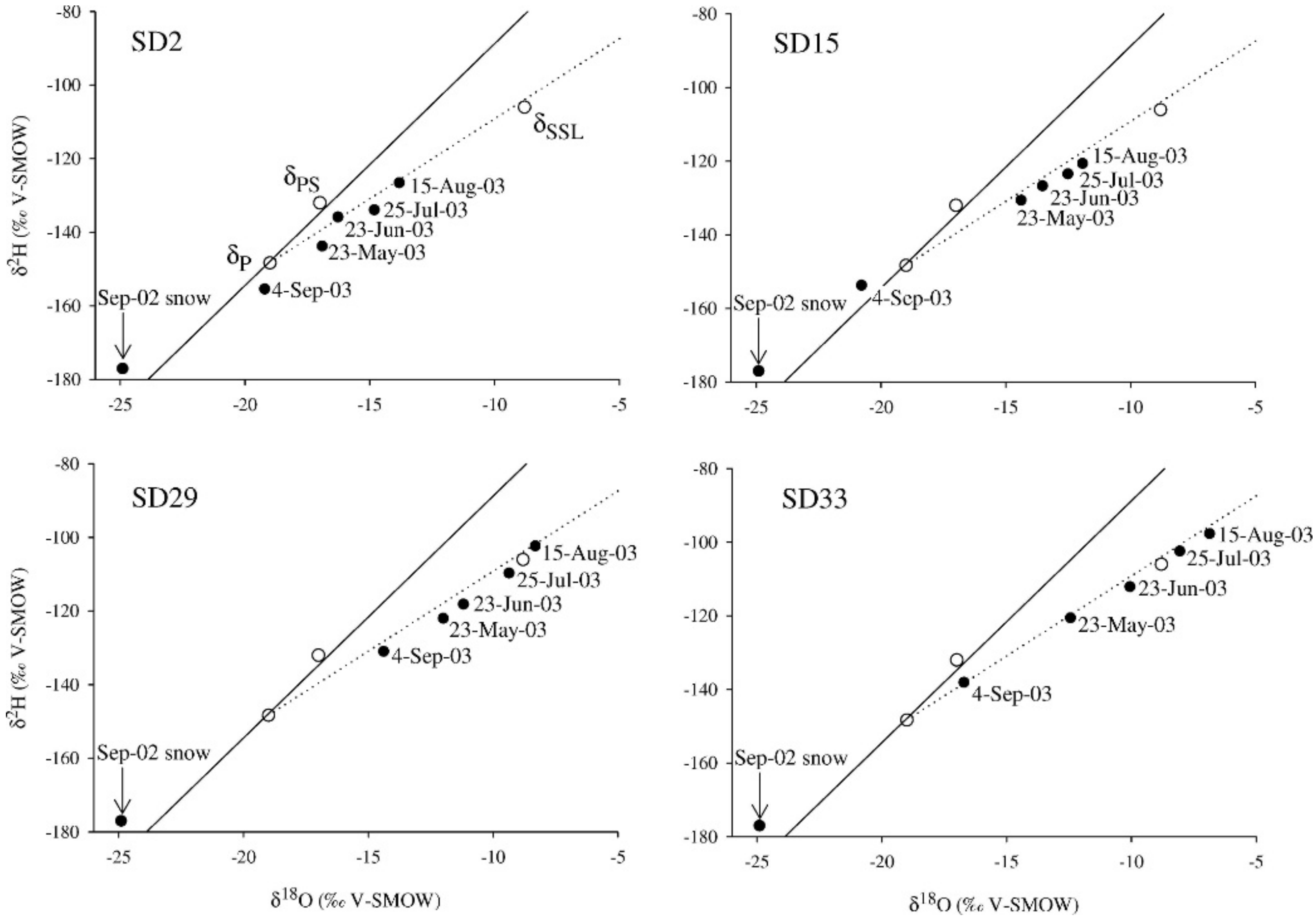

FIGURE 10. Isotopic evolution of four SRD lakes (SD2, SD15, SD29, and SD33) during the 2003 thaw season, showing evaporative enrichment prior to 15 August 2003 and subsequent isotopic depletion in response to 39 mm of late season precipitation between 15 August 2003 and 03 September 2003. Isotopic compositions are superimposed on the 2003 climate isotopic framework (see Fig. 2). Isotopic framework parameters are shown as open circles.

network and Great Slave Lake. By late in the thaw season, evaporative enrichment blurred the distinction between flooded and non-flooded lakes and was the dominant process controlling most lakewater balances. However, in lakes that are connected, exchange with Great Slave Lake or the Slave River governed lakewater isotopic signatures. While results from the 2003 sampling campaigns were not capable of showing SRD-wide effects of thaw season precipitation on delta lakes, evidence from selected lakes suggests that during a very wet season, precipitation in the SRD would have the capacity to significantly affect lakewater isotopic signatures and play a potentially significant role in maintaining lakewater balances across the entire delta.

A lake's geographic position in the delta is a major determinant of the relative roles of river flooding, snowmelt, evaporation, and Slave River or Great Slave Lake exchange on lakewater balances. Isotopic evolution of lakes in the active part of the delta was most strongly controlled by spring flooding until late in the thaw season, when evaporative enrichment dominated. Lakes in the apex zone of the SRD were affected by spring snowmelt, and by early summer, in the absence of significant summer precipitation, the dominant process controlling their lakewater balances was evaporation. For lakes in direct communication with the Slave River or Great Slave Lake, exchange between the lake basin and external water dominated water balance conditions throughout the thaw season.

While biogeographical zones developed for the SRD by English et al. (1997) do reflect the variability observed in the isotopic evolution of SRD study lakes, a hydrologically based classification scheme for delta lakes is a more appropriate frame of reference from which to describe SRD hydrology. This study has revealed that levee height, and consequently flood susceptibility, is not the only factor governing SRD lakewater balances. Based on the data presented here, three hydrologic classes of lakes can be identified in the SRD based on dominant hydrologic inputs and outputs in 2003 (Table 2): (1) flood-dominated lakes in the active part of the delta; (2) evaporation-dominated lakes in the apex zone

TABLE 2

Hydrologic inputs and outputs from lakes in the SRD, based on hydrologically inferred zonation, where R = river inputs during elevated (spring flood) flow conditions (R_F) and normal summer flow conditions (R_N), S = catchment-sourced snowmelt inputs, P = thaw season precipitation, O = surface outflow during elevated (spring flood) flow conditions (O_F) and normal summer flow conditions (O_N), and E = surface water evaporation. Dominant processes are shown in bold. The role of groundwater in lakewater balances is likely minimal, as the SRD is situated in a zone of discontinuous permafrost and lowland drainage is generally poor (Day, 1972).

	SRD ZONE		
	Flood-dominated	Evaporation-dominated	Exchange-dominated
Inputs	$\mathbf{R_F}$ + S + P	S + **P**	$\mathbf{R_F}$ + $\mathbf{R_N}$ + S + P
Outputs	O_F + **E**	**E**	$\mathbf{O_F}$ + $\mathbf{O_N}$ + E

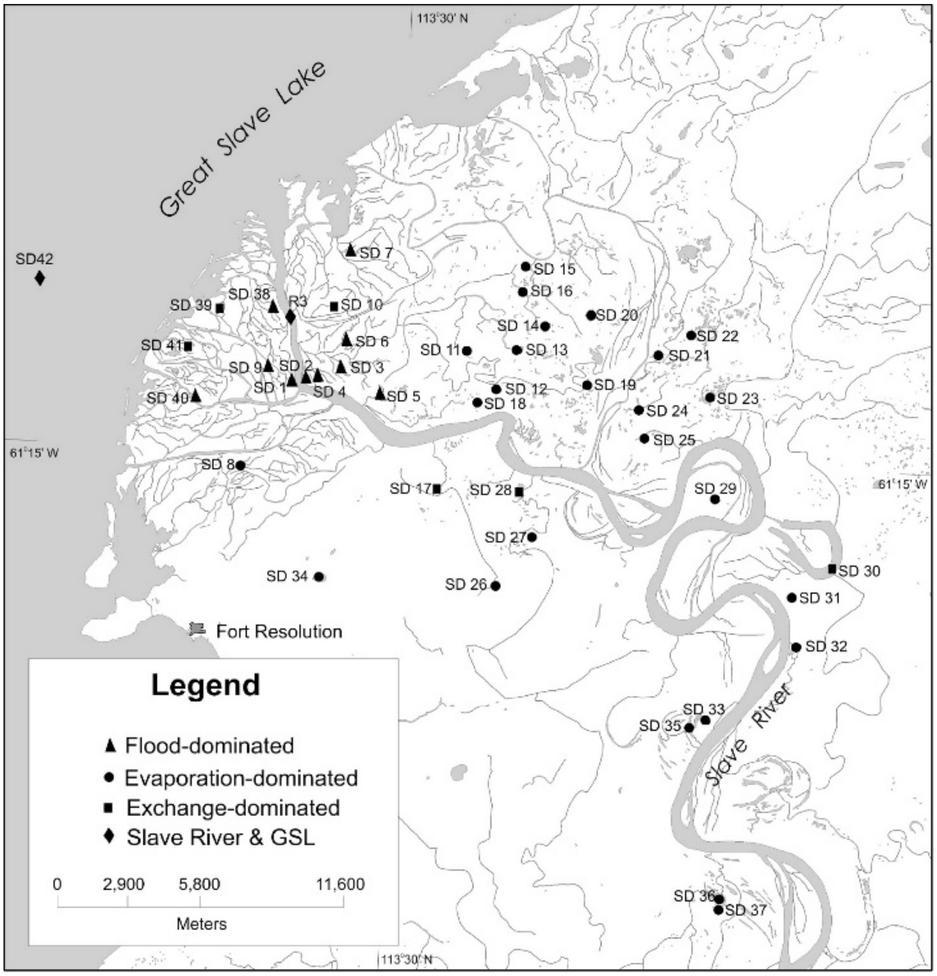

FIGURE 11. SRD lakes classified based on dominant hydrologic inputs and outputs during the 2003 thaw season.

of delta; and (3) Great Slave Lake and Slave River–exchange dominated lakes in the active delta and along the Slave River (Fig. 11). Late-season isotope data also indicate that precipitation inputs to evaporation-dominated lakes have the potential to significantly affect lakewater balances, and thus in very wet summers, precipitation inputs could dominate lakewater balances in many delta lakes. Redefining the classification of SRD lakes based on the three categories described above incorporates the strongest influences on lakewater balances observed during the 2003 thaw season and emphasizes that local snowmelt input is an important contributor to maintaining lakewater balances in the older delta.

SD8 (Willow Lake) provides an excellent example of the appropriateness of this improved classification scheme. SD8 falls in the mid-delta biogeographical zone, and consequently would be expected to flood every five to seven years (Prowse et al., 2002). However, unlike other mid-delta lakes, SD8 was not flooded in the spring of 2003 (Fig. 4a). Based on the hydrologically based classification scheme developed here, SD8 is considered an evaporation-dominated lake, rather than a flood-susceptible mid-delta lake. The channel next to SD8 was historically a major distributary channel in the delta, before shifts in flow patterns reduced its discharge. As a result of former high flows in the channel adjacent to SD8, levees were built up to heights that now impede flooding. As flow in the channel adjacent to SD8 declined, possibly in association with a major eastward shift in flow to ResDelta channel beginning in 1966 (Gibson et al., 2006a), the susceptibility of SD8 to Slave River distributary flooding has been greatly reduced. Currently, SD8 is evaporation-dominated (Fig. 11), and flooding no longer plays a prominent role in its water balance, as was suggested by the former biogeographical classification.

Using this new hydrologically based classification scheme, preliminary assessments and predictions of hydrological change in response to variations in climate or alterations of the river regime can be made. For example, a change in the magnitude or frequency of spring flooding will have the greatest effect on flood-dominated lakes. Increases or decreases in relative humidity or temperature will have the most significant effects on evaporation-dominated lakes. In very wet summers, precipitation inputs may dominate the water balances of lakes classed here as evaporation-dominated. Exchange-dominated lakes will be most affected by increases or decreases in Slave River flows during the thaw season or by changes in the frequency or magnitude of Great Slave Lake seiche events. Warmer, drier climate conditions and reduced flood frequency may cause flood-dominated lakes to behave hydrologically like evaporation-dominated lakes, while the latter may desiccate.

It is important to note that the classification scheme described above is based on one season of sampling, and the intensity of spring flooding, snowpack depth and density, and thaw season relative humidity, temperature, and precipitation will vary from year to year. For example, a 46-year discharge record for the Slave River (Fig. 12) shows peak discharge during spring 2003 (5370 $m^3\ s^{-1}$) is equivalent to average peak discharge (5391 $m^3\ s^{-1}$) measured over the period of record (Water Survey of Canada, 2006). Discharge conditions measured in 2003 were met or exceeded during 24 of the spring seasons monitored, while

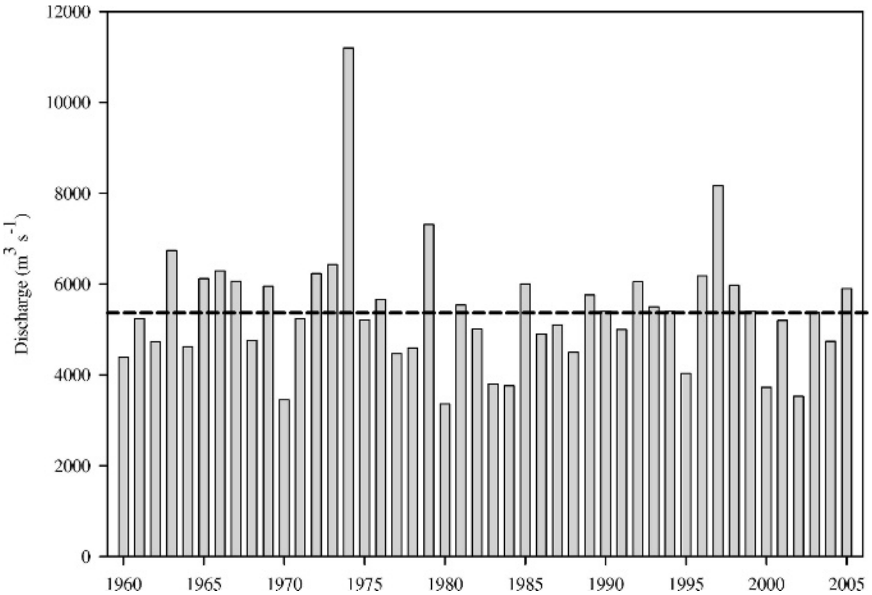

FIGURE 12. Peak Slave River discharge during the spring melt period, measured between 1960 and 2005 at Fitzgerald, Alberta (Water Survey of Canada, 2006). The dashed line represents peak discharge measured in the spring of 2003.

discharge was less than that of 2003 on 22 occasions. During years in which discharge is low, spring flooding is reduced or absent, and climatic conditions are similar to those that prevailed during 2003, isotopic enrichment from evaporation would dominate the water balances of all unconnected SRD lakes, including those classed here as flood-dominated. In years with large ice jams, spring flooding may be more widespread than that of 2003. Winters with deep snowpacks or rapid spring melting may increase the influence of catchment-sourced snowmelt on delta lakes. Variations in relative humidity and temperature during the thaw season may also affect the amount of evaporative enrichment a lake may undergo over the course of the thaw season. Alternatively, wet summers may suppress potential evaporation in delta lakes.

Summary and Future Directions

Analysis of water isotope tracers, supplemented by measurement of total inorganic suspended sediment, provides insight into hydrological processes that controlled SRD lakewater balances during the 2003 thaw season. Results differentiate the relative roles of flooding from the Slave River, exchange with Great Slave Lake, snowmelt, and thaw season precipitation as input sources, as well as evaporative loss. Distinguishing hydrological characteristics in our survey are used to identify three lake types in the SRD. The water balances of *flood-dominated lakes* in the active delta were strongly influenced by floodwater derived from the Slave River during the spring melt. The hydrological impact of spring flooding in these lakes persisted well into mid-summer, offsetting the isotopic effects of evaporation. *Evaporation-dominated lakes* in the apex zone of the delta received snowmelt input in the spring, but evaporation rapidly became the overriding process controlling lakewater balances by early summer. Late season precipitation also played a strong role in the water balances of selected evaporation-dominated lakes. *Exchange-dominated lakes* along the fringes of the outer delta and adjacent to the upstream reaches of the Slave River possessed variable water balances throughout the thaw season, determined mainly by the strength of connection arising from Great Slave Lake seiche events or Slave River inflow. Notably, while our results confirm that flooding from the Slave River is an important supplier of water to the active delta (English et al., 1997; Prowse et al., 2002), this study has revealed that snowmelt input is a key contributor to maintaining lakewater balances in the older apex zone of the delta, and is also likely a key water source to lakes in the active delta during years in which no flooding occurs.

Results from this initial survey highlight the utility of water isotope tracers as an efficient, semi-quantitative approach for examining the behavior of lakewater balances with respect to a range of hydrological processes over a broad fluvial-deltaic landscape. Thus, a solid foundation has been developed to characterize interannual variability in lakewater balances from isotopic measurements obtained over multiple years, and to assess the impact of variable hydroclimatic conditions. These subsequent analyses will also have implications for contemporary hydroecological studies in the SRD, and will provide important constraints for ongoing multi-proxy paleolimnological investigations. Collectively, insights gained will contribute to understanding both contemporary water balance conditions and the evolution of hydroecological conditions in the SRD, necessary for anticipating future hydroecological trajectories in the context of hydroclimatic variability and change.

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Appendix A

Isotopic framework parameters are calculated using approaches described in detail in Edwards et al. (2004b), Gibson and Edwards (2002), Gonfiantini (1986) and Barnes and Allison (1983), and are based on the linear resistance model of Craig and Gordon (1965). Values for 2003 are summarized in Table A1.

TABLE A1

All values used for calculations of the isotopic framework for the 2003 thaw season, with references and equation numbers where appropriate.

	Value	Data source	Equation
h (%)	62.8	Environment Canada (2002)	
T (°C)	13.4		
α^*_{L-V} (^{18}O, ^{2}H)	1.0104, 1.0925		1, 2
ε^*_{L-V} (^{18}O, ^{2}H) (‰)	10.4, 92.5		3
ε^*_{K} (^{18}O, ^{2}H) (‰)	5.3, 4.7		4, 5
S	4.1		6
d	−69.7		7
$\delta^{18}O_{AS}$, $\delta^{2}H_{AS}$ (‰)	−27.3, −208		8
$\delta^{18}O^*$, $\delta^{2}H^*$ (‰)	−2.6, −76		9
$\delta^{18}O_{E-GSL}$, $\delta^{2}H_{E-GSL}$ (‰)	−42.8, −234		10
$\delta^{18}O_{SSL}$, $\delta^{2}H_{SSL}$ (‰)	−8.8, −106		
$\delta^{18}O_{P}$, $\delta^{2}H_{P}$ (‰)	−19.0, −148	Fort Smith CNIP Station	
$\delta^{18}O_{PS}$, $\delta^{2}H_{PS}$ (‰)	−17.0, −132	Gibson and Edwards (2002)	

Equilibrium liquid-vapor isotopic fractionation (α^*) is calculated from equations given by Horita and Wesolowski (1994), where

$$1000 ln\alpha^* = -7.685 + 6.7123(10^3/T) - 1.6664(10^6/T^2) + 0.35041(10^9/T^3) \quad (1)$$

for $\delta^{18}O$ and

$$1000 ln\alpha^* = 1158.8(T^3/10^9) - 1620.1(T^2/10^6) + 794.84(T/10^3) - 161.04 + 2.9992(10^9/T^3) \quad (2)$$

for δ^2H, where T represents the interface temperature in degrees Kelvin. Equilibrium separation between the liquid and vapor phases (ε^*) is expressed in decimal notation by

$$\varepsilon^* = (\alpha^* - 1). \quad (3)$$

Kinetic separation (ε_K) is given in decimal notation by

$$\varepsilon_K = 0.0142(1 - h) \quad (4)$$

for $\delta^{18}O$ and

$$\varepsilon_K = 0.0125(1 - h) \quad (5)$$

for δ^2H, where h is relative humidity in decimal notation (Gonfiantini, 1986).

The slope (S) and intercept (d) of the local evaporation line can be calculated using the approach of Barnes and Allison (1983), formulated for δ, ε, and h values in decimal notation as

$$S = \frac{\alpha^{*2}\left[\left(\varepsilon_K^2 + \varepsilon^{*2}/\alpha^{*2}\right)\left(1 + \delta_P^2\right) - h\left(\delta_P^2 - \delta_{AS}^2\right)\right]}{\alpha^{*18}\left[\left(\varepsilon_K^{18} + \varepsilon^{*18}/\alpha^{*18}\right)\left(1 + \delta_P^{18}\right) - h\left(\delta_P^{18} - \delta_{AS}^{18}\right)\right]} \quad (6)$$

and

$$d = \delta_P^2 - S\delta_P^{18} \quad (7)$$

where δ_P and δ_{AS} are the respective isotopic compositions of input water and ambient atmospheric moisture. The latter is assumed to be in equilibrium with evaporation-flux-weighted (~summer) precipitation, as given by

$$\delta_{AS} = \frac{\delta_{PS} - \varepsilon^*}{\alpha^*} \quad (8)$$

(Gibson and Edwards, 2002).

The LEL extends from δ_P to the limiting non-steady-state composition (δ^*) of a water body approaching complete desiccation, calculated from

$$\delta^* = \frac{h\delta_{AS} + \varepsilon_K + \varepsilon^*/\alpha^*}{h - \varepsilon_K - \varepsilon^*/\alpha^*} \quad (9)$$

for δ, ε and h values in decimal notation (Gonfiantini, 1986).

The calculated limiting steady-state isotopic composition (δ_{SSL}) also provides a key datum on the LEL, representing the isotopic signature of a terminal lake in which evaporation exactly balances inflow. This can be obtained readily from the Craig-Gordon equation for the isotopic composition (δ_E) of the evaporating flux from a lake (δ_L) undergoing steady-state evaporation (also for δ, ε and h values in decimal notation)

$$\delta_E = \frac{(\delta_L - \varepsilon^*)/\alpha^* - h\delta_A - \varepsilon_K}{1 - h + \varepsilon_K} \quad (10)$$

for the special case in which $\delta_E = \delta_P$.

As noted in the text, δ values are conventionally multiplied by 1000 and expressed in per mil (‰).