

Hydroecological responses of the Athabasca Delta, Canada, to changes in river flow and climate during the 20th century

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ABSTRACT

We employ water-isotope tracers and multi-proxy paleolimnological records to characterize contemporary controls on water balances of floodplain lakes in the Athabasca Delta, Canada, within the context of its hydroecological evolution over the 20th century. The insight gained from these approaches is necessary to gauge the hydroecological resiliency of the Athabasca Delta to past and future changes in Athabasca River flow regime. Results obtained from three lakes located in different regions of the Athabasca Delta indicate that hydroecological conditions were strongly affected by an engineered meander cut-off on the Athabasca River in 1972, intended to maintain flow in the river main stem, and a natural bifurcation of one of the major distributaries (Embarras River) in 1982, in response to progressive overextension of the delta to the east. Climate warming and naturally declining river discharge have also contributed to directional change. Recent drying trends reconstructed from sediment cores at two of the three lakes are likely representative of rapidly evolving hydroecological conditions in the south-eastern sector, based on mapping of a recent high-magnitude ice-jam flood that failed to recharge this portion of the delta, while wetting in the region of the third lake due to increased frequency of river flooding reflects increasing diversion of Athabasca River flow northward. Our findings highlight the hydroecological sensitivity of the Athabasca Delta to changes in the magnitude and timing of discharge in the Athabasca River and heighten the need for informed management strategies to safeguard the integrity of this unique wetland ecosystem. Copyright © 2008 John Wiley & Sons, Ltd.

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INTRODUCTION

Natural and anthropogenic changes in river-flow regimes can have marked effects on downstream deltaic ecosystems and, in particular, the hydrological, limnological and ecological conditions that are critical for supporting biologically productive aquatic habitats (Junk, 2005). In complex aquatic ecosystems such as deltas, deciphering the relative roles of multiple stressors requires temporal and spatial perspectives on hydroecological variability, which are frequently unavailable even where routine ecosystem-monitoring programmes are in place. The absence of such fundamental knowledge of hydroecological behaviour over extended timescales and spatial dimensions presents a significant challenge for water resource managers to develop effective ecosystem stewardship policies.

For the Peace-Athabasca Delta (PAD), Canada (Figure 1), perceived effects of regulation of the Peace

River for hydroelectric production have long been a central focus in aquatic ecosystem health assessments and implementation of management strategies (e.g. PADPG, 1973; PADIC, 1987; PADTS, 1996; Gummer *et al.*, 2000; Prowse *et al.*, 2006). This reflects the widespread belief that alteration of the Peace River flow regime has affected the frequency and magnitude of spring ice-jam flooding, which is considered to play an important role in the water balance of many basins that are perched above, and disconnected from the complex channel network in the PAD (e.g. Prowse and Lalonde, 1996; Prowse and Conly, 1998, 2000). These basins and their extensive shorelines sustain productive and diverse wildlife and vegetation communities that are of cultural and historical importance to local First Nations residents of Fort Chipewyan. Situated largely within Wood Buffalo National Park at the confluence of the Peace and Athabasca rivers at the western end of Lake Athabasca, the PAD has acquired global recognition as a Wetland of International Significance (Ramsar Convention on Wetlands) and a UNESCO (United Nations Educational, Scientific, and Cultural Organization) World Heritage Site.

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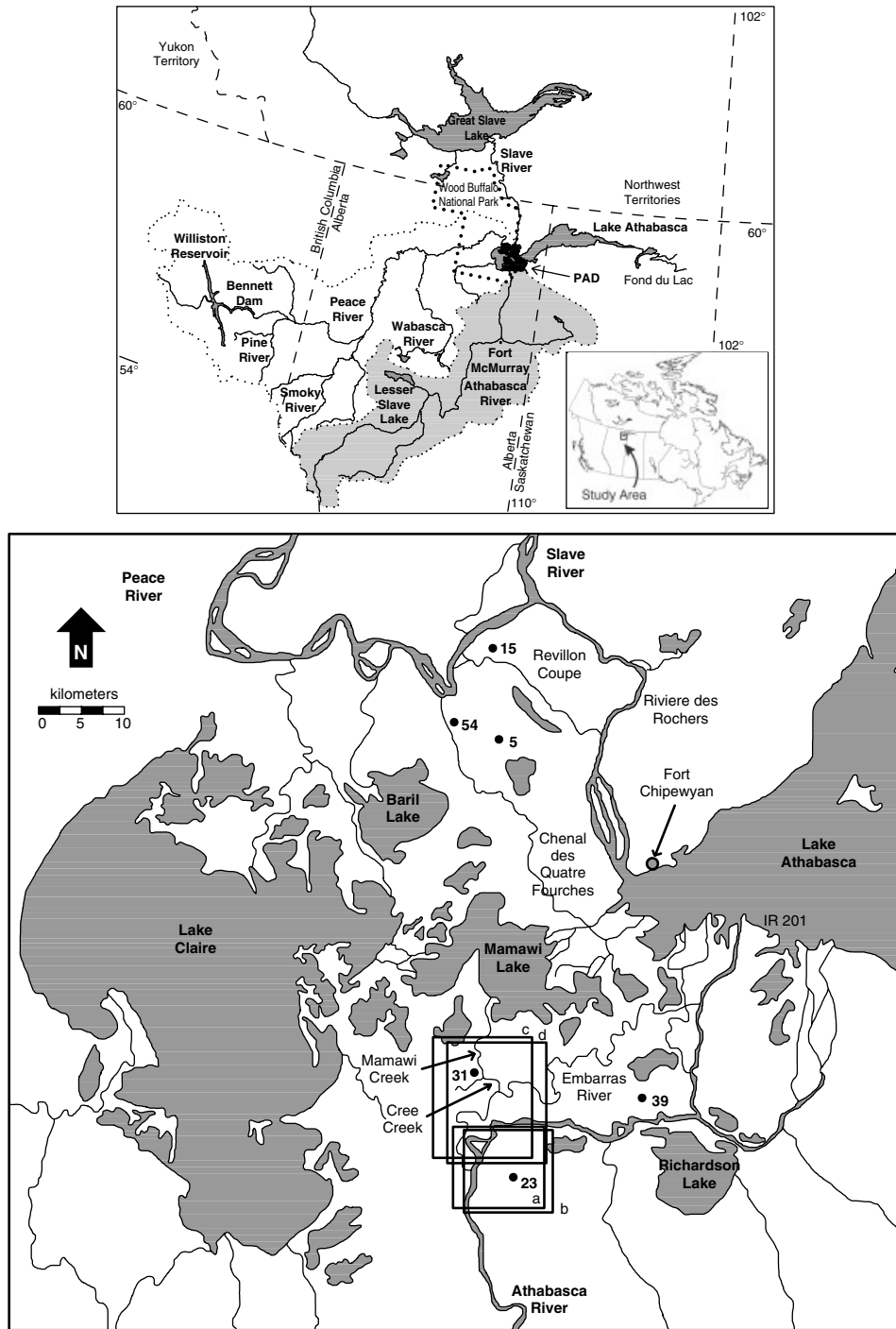


Figure 1. The Peace-Athabasca Delta (PAD) is located in north-eastern Alberta, Canada, to the west of Lake Athabasca. The Athabasca River originates in the Columbia Icefield in the Rocky Mountains of Alberta, 1300 river km upstream of the PAD, and drains an area of ~160 000 km² before entering lakes Athabasca and Mamawi via the main stem and distributaries (Peters, 2003). The Peace River drainage basin is also shown. Hydrological and paleolimnological records discussed here are from aquatic basins PAD 23, PAD 31, and PAD 39 in the southern Athabasca Delta. Paleolimnological records from ‘Spruce Island Lake’ (informal name; PAD 5) and from oxbow lakes ‘Pete’s Creek’ (local name; PAD 15) and ‘Horseshoe Slough’ (local name; PAD 54) in the northern Peace sector of the delta have been reported previously (Wolfe *et al.*, 2005, 2006b). Boxes in the lower map identify aerial photo coverage in Figure 3.

Over the past several years, we have been conducting extensive multidisciplinary research incorporating modern survey and process studies in addition to multi-proxy analyses of lake-sediment cores to gain better understanding of past and present hydroecology of the PAD. Results from contemporary investigations have included quantitative hydrological characterization of distinctive landscape

sectors in the PAD based on a novel integration of lake water stable-isotope composition and chemical parameters (Wolfe *et al.*, 2007b). This study established the basis to predict responses of limnological and ecological conditions to past and future hydrological change and set the stage for acquiring multi-proxy lake-sediment records, which have provided an important opportunity to

further develop understanding of the main processes regulating hydroecological dynamics of the PAD and insight into its ongoing evolution. For example, analysis of laminated sediments of oxbow lakes showed that Peace River flood frequency has been highly variable over the past ~300 years, but in decline for many decades beginning as early as the late 1800s (Wolfe *et al.*, 2006b). At a more elevated site, multi-proxy analyses provided evidence for seasonal to periodic desiccation in response to locally drier climatic conditions and reduced flooding during the peak of the Little Ice Age in the 1700s (Wolfe *et al.*, 2005). During the actual filling of the Williston Reservoir in 1968–1971, reduction in Peace River discharge almost certainly exacerbated the short-term effects of climatic and hydrologic drought at this time in western Canada (Timoney, 2002). However, paleolimnological reconstructions from several sites have yielded no compelling evidence to suggest that ongoing flow regulation of the river has had any discernable lasting effects on the hydroecology of the northern, Peace sector of the delta. Rather, changes in the hydroecological state of the Peace sector appear to be driven predominantly by local and regional climatologic variability at interannual to decadal timescales, and by ongoing warming, drying, and naturally declining Peace River discharge over the past century (also in Edwards *et al.*, 2004; Hall *et al.*, 2004; Wolfe *et al.*, 2006a).

In comparison to the numerous studies that have assessed relationships between the regulated flow regime of the Peace River and contemporary hydroecological conditions in the PAD (e.g. Townsend, 1975; Prowse and Lalonde, 1996; Timoney *et al.*, 1997; Leconte *et al.*, 2001; Peters and Prowse, 2001; Prowse *et al.*, 2006; Wolfe *et al.*, 2006b), far less attention has been given to the hydrological role of the unregulated Athabasca River in maintaining ecosystem structure (e.g. Peters and Prowse, 2006; Peters *et al.*, 2006b) yet it provides the largest direct inflow of water to the PAD and Lake Athabasca. As a result, the southern Athabasca sector of the PAD differs markedly from the northern Peace sector; the former is actively prograding into Lake Athabasca and receives frequent flood inputs from the Athabasca River and its distributaries while the latter is a relict deltaic landscape that only receives widespread flooding from the Peace River during episodic ice jams that cause flow reversals along distributary channels connecting Lake Athabasca with the Peace River (Prowse and Lalonde, 1996; Peters *et al.*, 2006b). Thus, there is considerable potential for large-scale hydroecological changes to occur in the Athabasca Delta in response to changes in the flow of the Athabasca River. Of particular concern are the effects on the Athabasca Delta that could result from declining flow generation in the Rocky Mountains (Demuth and Keller, 2006) combined with increases in the allocation of Athabasca River flow to support accelerated growth of the Alberta oil-sands industry (Schindler and Donahue, 2006; Schindler and Smol, 2006). Such assessments and predictions, however, are hampered by the absence of knowledge concerning the

response of the delta ecosystem to past flow regime changes of the Athabasca River.

Variability in several factors can cause hydroecological changes in deltaic environments. These include climate, river discharge, and geomorphic controls on distributary channel flow. In the Athabasca Delta, recent channel modifications have altered the flow of the Athabasca River and its distributaries within the Athabasca Delta, which are superimposed on variable but generally declining Athabasca River discharge over the past ~40 years (Schindler and Donahue, 2006). Here we assess the hydroecological effects of these flow regime changes in the Athabasca River on the Athabasca Delta in the context of natural variability of the 20th century, a time frame that encompasses recent atmospheric warming and drying (CANGRID, 2000; Bailey and Edwards, unpublished). Our approach integrates knowledge of present and past hydrological conditions developed from use of water-isotope tracers and multi-proxy paleolimnological records from three shallow lakes in the Athabasca Delta. Results of this study provide the basis for anticipating future hydroecological changes in the Athabasca Delta. The practicality of such forecasting is particularly relevant to water resource managers responsible for protecting the ecological integrity of the Athabasca Delta, given the likelihood that Athabasca River discharge will continue to decline in the coming decades.

STUDY AREA

Climate

Climate of the PAD is characterized by long, cold winters and relatively short, warm summers. Mean annual air temperature is -1.9°C , mean January air temperature is -23.2°C and mean July air temperature is 16.7°C based on 1971–2000 climate normals (Environment Canada Weather Station at Fort Chipewyan, Alberta). Precipitation averages 391.7 mm annually, with about 59% falling as rain during the May–September period. During the 5-year monitoring period in which we have been conducting contemporary hydroecological studies, average ice-free season conditions were generally warmer and drier in 2001, drier in 2003, cooler and drier in 2004, and cooler and wetter in 2002 and 2005 compared to climate normals, with highly variable monthly precipitation in 2002, 2004 and 2005 (Figure 2).

River hydrology

The PAD is composed of three deltaic regions including the relict Peace to the north ($\sim 1680\text{ km}^2$), active Athabasca to the south ($\sim 1970\text{ km}^2$) and the much smaller Birch to the west ($\sim 170\text{ km}^2$; PADPG, 1973). These contributing basins have coalesced at the west arm of Lake Athabasca to form several large shallow lakes (Claire, Baril, and Mamawi lakes) in the centre of the PAD (Figure 1).

The river hydrology of the northern Peace sector of the delta is controlled by distributary channels that can

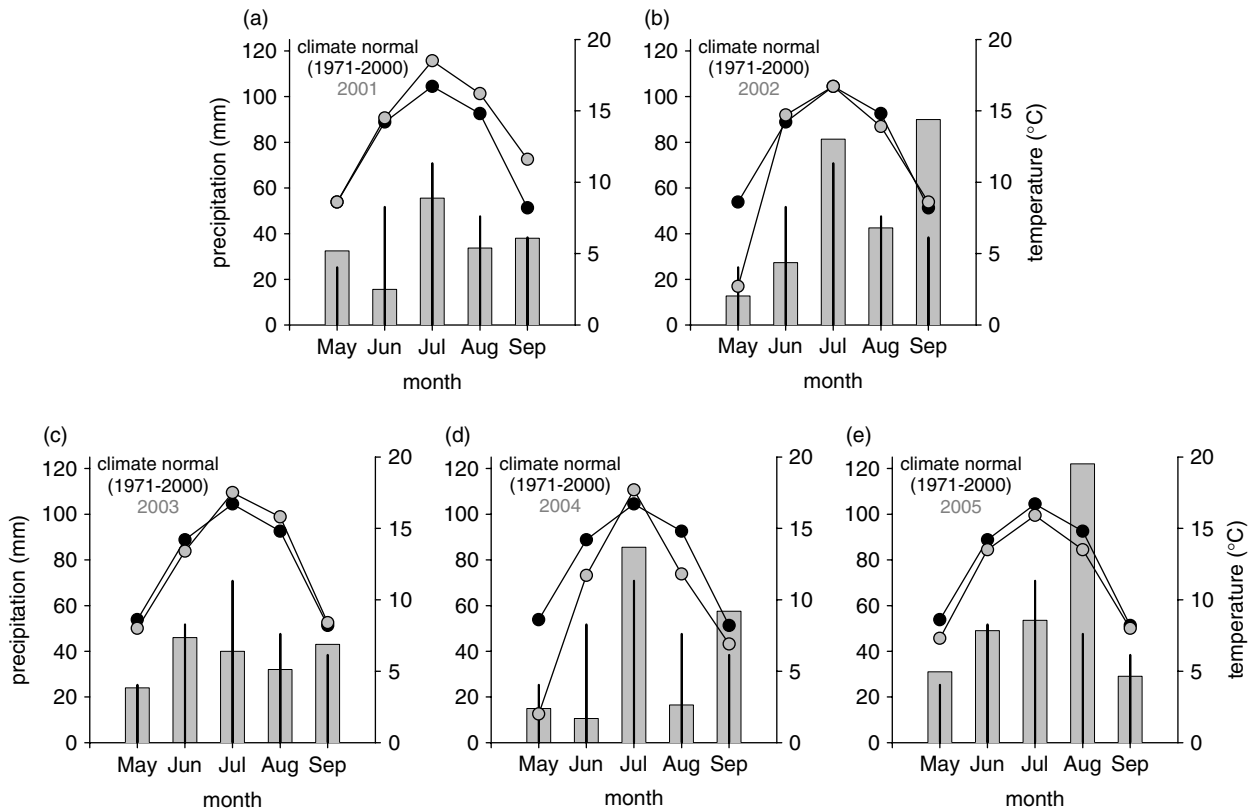


Figure 2. Mean monthly air temperature (circles) and precipitation (bars) from the Environment Canada Weather Station (ID 3072658) at Fort Chipewyan, Alberta, comparing values for the monitoring period (2001–2005; grey circles and thick grey bars) to 1971–2000 climate normals (black circles and thin black bars).

experience flow reversals. Under normal flow conditions, Lake Athabasca and the Athabasca River drain northwards via the Rivière des Rochers, Revillon Coupé and Chenal des Quatre Fourches to the Peace River where they join to form the Slave River (Figure 1). During high-water events on the Peace River, accentuated by ice jams that occasionally develop near the terminus of the river in spring (April/May), water can flow southwards from the Peace River through these channels and cause overland flooding of the northern Peace sector of the PAD. Major spring ice-jam floods of the northern Peace sector last occurred in 1996 and 1997.

In contrast, the Athabasca River flows directly into the southern part of the delta (the Athabasca Delta) and divides into a number of distributaries that flow north-eastward into Lake Athabasca including the Embarras River (Figure 1). Since our monitoring began in the fall of 2000, we have observed floods of varying magnitude and spatial extent in the Athabasca Delta during the spring (2003, 2005) as a result of ice jams that developed on the Athabasca and Embarras Rivers and in the summer (2001, 2004) due to high flows on the Athabasca River likely in response to high precipitation events and snowmelt run-off from elevated regions near the headwaters.

During the past 35 years, both engineered and natural diversions have altered the distribution of river flow in the Athabasca Delta. In 1972, impending avulsion of the Athabasca River into the Embarras River at the

upstream reaches of the Athabasca Delta was prevented by excavation of a channel across a tight meander bend in the Athabasca River (the 'Athabasca River Cut-Off'; Figure 3(a) and (b)). The construction of the channel alleviated concerns, albeit temporarily, of substantial flow bypassing Chipewyan Indian Reserve 201 (Figure 1) to the north-east if a natural avulsion had been allowed to develop. Ten years later, however, natural bifurcation of the Embarras River farther downstream diverted flow north-west through Cree and Mamawi creeks (the 'Embarras Breakthrough'; Figure 3(c) and (d)), which discharge into Mamawi Lake in the central portion of the PAD. This event resulted in a significant redistribution of flow in the Athabasca Delta. Estimates suggest that 58% of the flow of the Embarras River has been redirected north-west to Mamawi Lake instead of to Lake Athabasca, a value that approaches 100% during conditions of low-flow (De Boer *et al.*, 1994). The former estimate comprises about 6% of the total flow of the Athabasca River, and has nearly doubled the inflow to Mamawi Lake (PADTS, 1996). These changes are superimposed on variable but declining Athabasca River discharge downstream of Fort McMurray over the past ~40 years (Schindler and Donahue, 2006).

Lake hydrology

Hydrological conditions of the numerous shallow, aquatic basins in the PAD (collectively referred to as lakes) vary

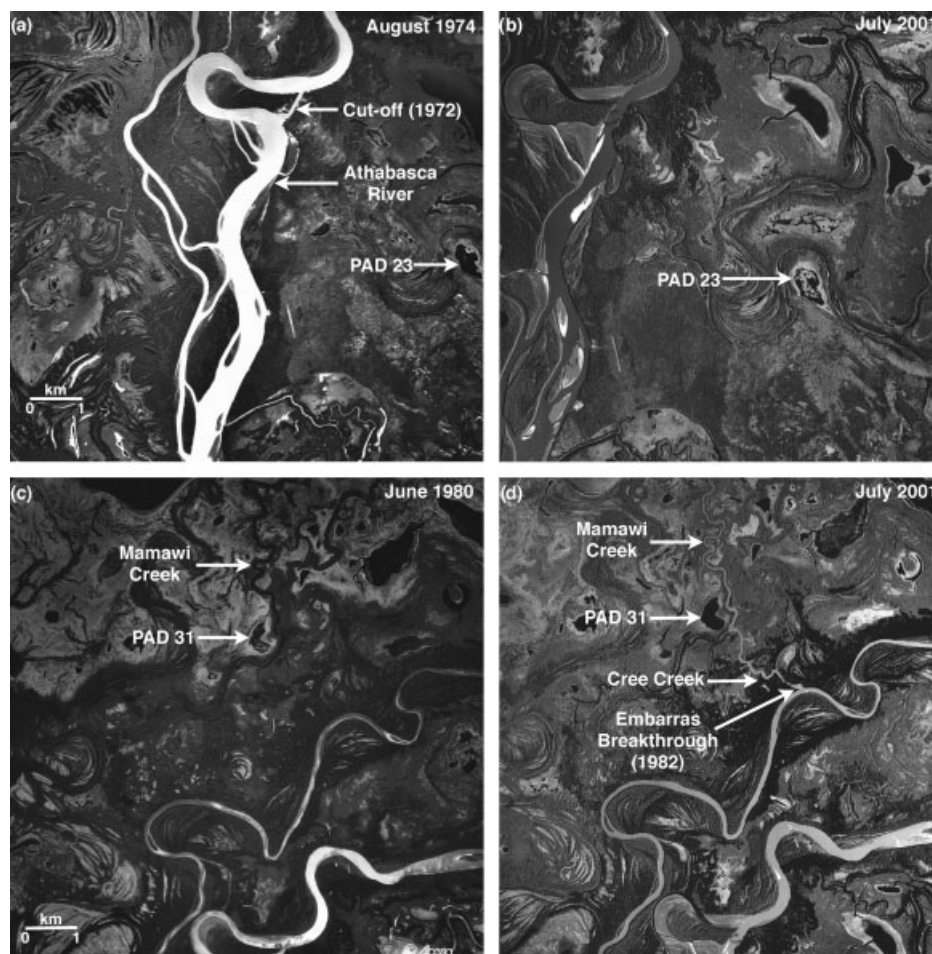


Figure 3. Historical aerial photos of (a), (b) the 'Athabasca River Cut-Off', an excavated channel constructed in 1972 to prevent an avulsion of the Athabasca River into the Embarras River and which has become incised over the past 30 years, and (c), (d) the 'Embarras Breakthrough', a natural avulsion that directed flow from the Embarras River to Cree and Mamawi creeks. Study basins PAD 23 and PAD 31 are also shown.

across a broad spectrum because the relative proportions of individual fluxes comprising the water balance can differ markedly among lakes. The nature and frequency of river connection have often been considered most important and form the basis of qualitative-based hydrological classifications of PAD lakes. These classification schemes typically employ a terminology that includes open-, restricted- and closed-drainage basins mainly reflecting declining relative influence of river water on the lake water balance (PADPG, 1973; Pietroniro *et al.*, 1999).

We have utilized water-isotope tracers and limnological variables to provide a quantitative framework for classifying ~60 lakes in the PAD into these previously defined drainage types based on hydrolimnological conditions at the time of freeze up in 2000 (Wolfe *et al.*, 2007b; Table I). Our analysis revealed the wide range of limnological conditions that also characterize these basins, their close association with the hydrological classification system, as well as a new fourth drainage type with unique hydrolimnological properties. Results from this end-of-thaw-season sampling indicated that open-drainage basins were chemically dilute, similar to the

river, having relatively depleted heavy-isotope composition (O, H), low alkalinity and concentrations of nitrogen, dissolved organic carbon (DOC) and ions, and high minerogenic turbidity. These basins are located mainly in the low-lying central portion of the delta where many of the rivers and creeks that constitute the complex channel network of the PAD discharge into broad, shallow lakes. In contrast, closed-drainage basins were isotopically-enriched due to the importance of evaporation on the water balance and had high alkalinity, high concentrations of dissolved nitrogen, DOC and ions and low minerogenic turbidity. These basins populate the Peace sector of the delta and receive widespread river input only during periodic ice-jam flood events on the Peace River, and thus input sources are dominated by precipitation (including snowmelt run-off). Restricted-drainage basins were intermediate in isotopic and chemical composition and are located mainly in the Athabasca Delta, where the landscape is characterized by more frequent flooding from the Athabasca River and its distributaries. The input of river water is the primary hydrological process that controls lake water balances in these basins. A new fourth category was identified, rainfall-influenced basins, which were chemically similar to closed-drainage basins, but with higher conductivity and concentrations

Table I. Hydrological classification and limnological characteristics of lakes in the Peace–Athabasca Delta (PAD) indicating primary sources of hydrological input and output based on results from Wolfe *et al.* (2007b) and simplified from equations provided by Prowse *et al.* (1996) and Peters (2003). Dominant hydrological processes are identified in bold type. The three basins utilized in this study represent three of the four drainage types. Note that groundwater is thought to be a minor component of lake water balances because horizontal gradients between lakes are very low (PADPG, 1973; Prowse *et al.*, 1996) and because discontinuous permafrost underlies the region, which likely restricts local groundwater movement.

	Peace–Athabasca Delta hydrological lake categories			
	Open-drainage	Restricted-drainage (e.g. PAD 31)	Rainfall-influenced (e.g. PAD 39)	Closed-drainage (e.g. PAD 23)
Hydrological characteristics				
Hydrological inputs	P + R_L + R_E + R_F	P + R_E + R_F	P + R_E + R_F	P + R_F
Hydrological outputs	O + E	O + E	E	E
Limnological characteristics				
[Dissolved N]	Low	Intermediate	High	Very high
[Dissolved organic C]	Low	Intermediate	Very high	High
[Chlorophyll <i>a</i>]	Low	High	Low	High
[Ions]	Low	High	Very high	High
Alkalinity	Low	Intermediate	High	High
Minerogenic turbidity	High	Intermediate	Low	Low

P, precipitation falling directly on the lake plus surface and subsurface catchment run-off; R, river input under low-flow (R_L), elevated-flow (R_E), and flood (R_F) conditions; O, surface outflow; E, open-water evaporation.

of calcium and sodium, and lower concentrations of silica and chlorophyll due to the overriding influence of summer rainfall on the basin-water balance and chemistry. Rainfall-influenced basins are found mainly in the central portion of the delta adjacent to the large open-drainage basins and occupy shallow depressions in the landscape (depth < 50 cm).

Site descriptions

Interpretation of lake water-isotope composition time series and multi-proxy paleolimnological records from three shallow lakes in the Athabasca Delta form the basis of this study. The basins, as revealed by water-isotope tracer measurements presented in a section further below, represent three of the four major drainage types (Table I) and are geographically distributed to assess the hydroecological effects resulting from recent changes in Athabasca River flow patterns (Figures 1 and 3; Schindler and Donahue, 2006). Collection and analysis of sediment cores from the large, shallow open-drainage basins have been avoided because of the greater potential for physical sediment mixing to have caused disturbance of the stratigraphic record in these lakes compared to the other drainage-basin types.

'PAD 23' (unofficial name; 58°23.4'N, 111°26.6'W; 213.3 m asl) is a small (~18 ha), shallow (~1.7 m maximum water depth) basin situated to the south of a large meander of an abandoned river channel, 5 km south-east of the Athabasca River Cut-Off (Figure 3(a) and (b)). There are no active inflow or outflow channels. The basin is surrounded by sedges and a fringe of submerged and floating mosses. The lowland area beyond the shoreline is dominated by stands of willow shrubs, while relict river levees near the north end of the basin support spruce and poplar trees. To the south lies an elevated sand dune area stabilized by pine forest.

We have observed highly productive conditions in the basin characterized by dense growth of the floating-leaved macrophyte *Nuphar varietatum* and submerged macrophytes *Potamogeton zosteriformis*, *Drepanocladus aduncus* and *Ceratophyllum demersum*.

'PAD 31' (local name: 'Johnny Cabin Pond'; 58°29.8'N, 111°31.2'W; ~206 m asl) is a small (~25 ha), shallow (~1.4 m maximum water depth) basin located 150 m west of Mamawi Creek, 3 km downstream of the Embarras Breakthrough (Figure 3(c) and (d)), in an area of low relief dominated by marshes and willow swamps. There are no active inflow or outflow channels, although we have observed (and identified isotopically; given below) several floods that have inundated the basin with river water that has spilled over the banks of Mamawi Creek during both spring and summer high-water events. Highly productive conditions have been observed with extensive growth of submerged macrophytes dominated by *P. zosteriformis* and *Myriophyllum exalbescens*.

'PAD 39' (unofficial name; 58°28.0'N 111°10.5'W; 210.5 m asl) is a small (~55 ha), shallow (~0.8 m) basin located in a large, low-lying wetland area between the Athabasca and Embarras rivers, ~17 km downstream of the Embarras Breakthrough (Figure 1). There are no active inflow or outflow channels. Observations have documented high levels of productivity characterized by extensive growth of emergent plants (*Typha latifolia* and *Phragmites*), filamentous algae along the shoreline and dense beds of *Elodea* and *Potamogeton* covering most of the lake bottom.

METHODS

Lake water sample collection and isotope analyses

Water samples were collected at ~10-cm depth from PAD 23, PAD 31, and PAD 39, as well as the Athabasca

River (58°24'N; 111°31'W), on several occasions during the ice-free season between October 2000 and September 2005 to examine seasonal and interannual variability in lake water balances, including the role of river flooding, using water-isotope tracers. Water samples were collected in 30 ml high-density polyethylene bottles and transported to the University of Waterloo-Environmental Isotope Laboratory (UW-EIL) for determination of oxygen and hydrogen isotope composition using conventional techniques (Epstein and Mayeda, 1953; Coleman *et al.*, 1982). Results are expressed in standard δ -notation, which represent deviations in per mil (‰) 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 $^{18}\text{O}/^{16}\text{O}$ or $^2\text{H}/^1\text{H}$ ratio in sample and VSMOW. Results of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ analyses are routinely normalized to -55.5 and -428 ‰, respectively, for Standard Light Antarctic Precipitation (SLAP; Coplen, 1996). Analytical uncertainties are on the order of ± 0.2 ‰ for $\delta^{18}\text{O}$ and ± 2.0 ‰ for $\delta^2\text{H}$.

Collection of lake-sediment cores

Four sediment cores were collected near the centre of PAD 23 (core lengths ranged from 32.0 to 41.5 cm), PAD 31 (core lengths: 24.5–28.0 cm) and PAD 39 (core lengths: 27.5–34.0 cm) in June 2001 using a gravity corer (Glew, 1989) deployed from a floating platform and sectioned into 0.5-cm intervals (Glew, 1988) at a field house operated by Wood Buffalo National Park in Fort Chipewyan after transportation by helicopter. Replicate sediment cores were collected from each basin to provide sufficient material for multi-proxy paleolimnological analyses to reconstruct past hydroecological conditions. All analyses were conducted on consecutive 0.5-cm sediment intervals. These included radiometric measurements (^{210}Pb) and analyses spanning a broad range of physical (loss-on-ignition, texture and mineralogy), geochemical (organic carbon and nitrogen elemental and stable-isotope composition, cellulose oxygen-isotope composition) and biological (diatoms, pigments, and plant macrofossils) techniques. Analytical methods used for results reported here are briefly described below.

Geochronological analyses

To develop lake-sediment chronologies spanning the past ~ 100 – 150 years, samples from one of the gravity cores from each lake were analysed for ^{210}Pb at the Environmental Radiochemistry Laboratory, Department of Fisheries and Oceans, Winnipeg, Canada. Samples of dry sediment (1–3 g) were analysed from every 0.5-cm sediment interval for ^{210}Pb by leaching in 6N HCl in the presence of a ^{209}Po tracer, autoplating Po onto a silver disc (Flynn, 1968) and counting the disc on an alpha spectrometer to determine ^{210}Pb via its ^{210}Po daughter. The Constant Rate of Supply (CRS) model (Appleby, 2001), which assumes a constant flux of ^{210}Pb to the sediment and changing sedimentation rates, was used to establish the geochronology for the analysed

core from each lake. The resulting depth-age profile was applied directly to the additional gravity cores from each lake based on matching stratigraphic changes in loss-on-ignition at 550 °C (Hall *et al.*, 2004).

Geochemical analyses

Cellulose oxygen-isotope composition was determined following methods detailed in Wolfe *et al.* (2001, 2007a). Briefly, pretreatment consisted of acid washing with 10% (by volume) HCl at 60 °C to remove carbonate, followed by rinsing with deionized water, freeze-drying and sieving to remove coarse debris using a 500- μm sieve. Organic carbon content was measured on subsamples of the fine fraction by an elemental analyser. Additional treatment, involving solvent extraction, bleaching and alkaline hydrolysis was conducted to remove non-cellulose organic constituents, hydroxylamine leaching to remove iron and manganese oxyhydroxides, and heavy-liquid density separation using sodium polytungstate to concentrate the cellulose fraction. Cellulose oxygen-isotope composition was measured by a continuous flow— δ -isotope ratio mass spectrometer at the UW-EIL. Oxygen-isotope results are expressed as δ -values, as defined above, representing deviations in per mil (‰) from the VSMOW standard. Results are normalized to $\delta^{18}\text{O}_{\text{SLAP}}$, also as described above (-55.5 ‰; Coplen, 1996). Analytical uncertainty, based on sample duplicates, is ± 0.56 ‰ for PAD 23, ± 0.38 ‰ for PAD 31 and ± 0.83 ‰ for PAD 39. Lake water $\delta^{18}\text{O}$ values were reconstructed using a cellulose-water oxygen-isotope fractionation factor of 1.028 (Wolfe *et al.*, 2001).

Diatom analyses

Samples were prepared for diatom analysis by acid digestion following standard methods (Hall and Smol, 1996). Diatom valves were identified and counted (~ 400 per sample) at 1000 \times magnification using a Zeiss Axioskop II Plus light microscope fitted with differential interference optics (numerical aperture = 1.30). Taxonomic references for diatom identification include Foged (1981); Krammer and Lange-Bertalot (1986–1991) and Cumming *et al.* (1995). Diatom assemblages were summed into closed- and open-drainage hydrological categories based on contemporary relationships between these indicators and environmental variables, as determined from a surface-sediment dataset spanning 52 basins along a hydrological gradient in the PAD (Hall *et al.*, 2004).

Pigment analyses

Pigments were extracted from lyophilized sediments in an acetone/methanol/water mixture (85:10:5 by volume), dried under pure nitrogen gas and stored frozen (-20 °C) until analysis. Separation of pigments by high-performance liquid chromatography (HPLC) was undertaken on a Hewlett-Packard (HP) 1050 Series control module and a Rainin model 200 Microsorb C-18 column (5 μm particle size; 10 cm length) using the method of Mantoura and Llewellyn (1983), as modified by Leavitt

and Findlay (1994). An on-line HP 1050 scanning photodiode array spectrophotometer was used for the detection and quantification of pigments, which were identified on the basis of retention time and spectral characteristics relative to known standards (Leavitt and Hodgson, 2001). Pigment concentrations are expressed as nanomole pigment per gram of organic matter.

Macrofossil analyses

For plant macrofossil analysis, 10 cm³ subsamples of wet sediment were washed through a 125- μ m mesh screen with warm water. Material retained on the sieve was sorted in water using a binocular dissecting microscope at 8 \times to 40 \times magnification, and all identifiable macroremains were counted. Identifications were made with the aid of modern reference specimens and keys (including Jessen, 1955; Martin and Barkley, 1961; Berggren, 1969, 1981; Montgomery, 1977; and Artjuschenko, 1990). Data are presented as concentrations of macrofossils per 10 cm³ volume of sediment.

RESULTS AND INTERPRETATION

Hydrological controls on contemporary lake water balances

We have previously used water-isotope tracers to identify major controls on contemporary lake water balances in the PAD, as well as in the Slave River Delta downstream, because of the characteristic isotopic labelling that occurs as water passes through the hydrological cycle and the strong sensitivity of shallow lakes in these ecosystems to hydrological processes such as river flooding and evaporation (Edwards *et al.*, 2004; Wolfe *et al.*, 2005, 2007b; Brock *et al.*, 2007, 2008; Yi *et al.*, 2008). These studies have benefited from the distinct isotope signatures of snow, rain, and river water, which tend to plot near the Local Meteoric Water Line (LMWL: $\delta^2\text{H} = 6.7 \delta^{18}\text{O} - 19.2$), compared to lake waters, which lie close to a Local Evaporation Line (LEL; Figure 4). For the PAD, the predicted LEL based on available isotope and climate normal data is defined by $\delta^2\text{H} = 4.2 \delta^{18}\text{O} - 68.5$ (Wolfe *et al.*, 2007b), which represents the vector of all potential lake water balances fed by local amount-weighted annual precipitation (δ_p) and having undergone varying degrees of evaporation. Key points along the LEL include the isotope composition of a terminal (i.e. closed-drainage) lake fed by δ_p in hydrologic and isotopic steady state (δ_{SS} , where evaporation equals inflow), and the limiting isotope composition of a desiccating lake (δ^*). Characterization of dominant hydrological processes influencing the contemporary lake water balances of study basins PAD 23, PAD 31 and PAD 39 can be determined by superimposing results from isotope analysis of lake waters over the 5-year (2000–2005) collection period on $\delta^2\text{H} - \delta^{18}\text{O}$ plots and on $\delta^{18}\text{O}$ time-series diagrams, each constructed from parameters representing average ice-free season climatic conditions of the PAD (Figure 4; Wolfe *et al.*, 2007b). Results from the three lakes span broad ranges

of water-isotope composition (PAD 23 $\delta^{18}\text{O} = -13.3$ to -7.0‰ , $\delta^2\text{H} = -126$ to -97‰ ; PAD 31 $\delta^{18}\text{O} = -19.0$ to -10.8‰ , $\delta^2\text{H} = -151$ to -109‰ ; PAD 39 $\delta^{18}\text{O} = -14.1$ to -4.8‰ , $\delta^2\text{H} = -127$ to -84‰) with values from each basin positioned uniquely along the LEL reflecting differences in the relative importance of specific hydrological processes on the individual lake water balances as described below.

Floodwaters from the Athabasca River ($\delta^{18}\text{O} = -19.7$ to -16.8‰ ; $\delta^2\text{H} = -154$ to -136‰) were not observed to have entered PAD 23 during the 5-year monitoring period, consistent with clear separation between isotope values of the Athabasca River and PAD 23 (Figure 4(a)). Rather, tight clustering of PAD 23 lake water-isotope compositions about the LEL indicate the basin is largely fed by precipitation having a weighted mean isotope composition that closely approximates δ_p . Exceptions include several lake water samples obtained in the summer and fall that plot slightly above the LEL indicating influence from rainfall with isotope composition approximating average ice-free season precipitation (δ_{PS}). Seasonal patterns are evident in the accompanying $\delta^{18}\text{O}$ time-series plot, which are characterized by low $\delta^{18}\text{O}$ values in the spring due to the input of isotopically-depleted snowmelt ($\sim \delta_{PW}$ in Figure 4(a)), followed by a progressive increase in $\delta^{18}\text{O}$ values due to evaporation, and slight lowering of $\delta^{18}\text{O}$ values as a result of the input of summer and fall rain. Overall, isotope results indicate the water balance of PAD 23 is dominated primarily by input of snowmelt and rainfall balanced by evaporative loss as lake water-isotope values each summer tend to approach average ice-free season δ_{SS} ; hydrological processes characteristic of closed-drainage basins (Table I). Evaporative isotope enrichment beyond δ_{SS} in 2001 occurred during a particularly warm and dry summer (Figure 2(a)), as observed for PAD 39 (given below) and elsewhere in the PAD (Wolfe *et al.*, 2005). On the other hand, enrichment was curtailed before attaining δ_{SS} in 2005 because of very high precipitation accumulation in August of that year (Figure 2(e)).

In contrast to PAD 23, river floodwaters have been observed to enter PAD 31 on several occasions. These include during the spring of 2003 and 2005 as a result of ice jams that developed on the Athabasca and Embarras rivers and in the summers of 2001 and 2004 from high-water events on the Athabasca River and its distributaries (including Mamawi Creek). As indicated by the PAD 31 $\delta^{18}\text{O}$ time-series plot, similar PAD 31 and Athabasca River values during these events suggests nearly complete replacement of the basin with river water (Figure 4(b)). While evaporation during non-flood intervals of the ice-free season resulted in modest isotope enrichment of PAD 31 lake water along the LEL, the lake water failed to reach δ_{SS} during the 5-year monitoring period despite the fact that PAD 31 has no perennially active surface outlet. This includes the warm and dry year of 2001 in which strong evaporative isotope enrichment evident in the other non-flooded lakes (Figure 4(a) and (c)) did not occur in PAD 31 because of the effect of a summer

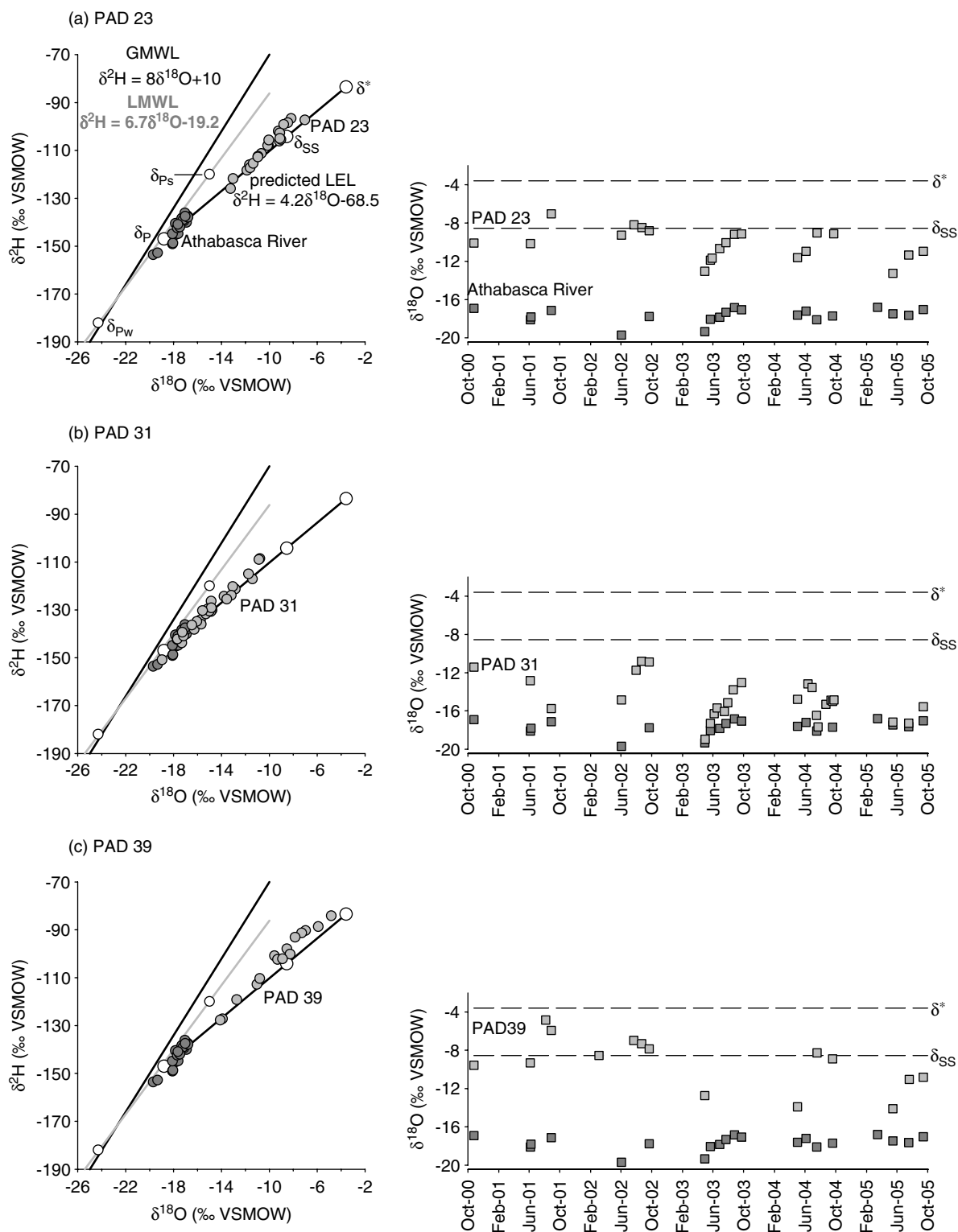


Figure 4. Lake water isotope results for (a) PAD 23, (b) PAD 31 and (c) PAD 39 as well as the Athabasca River shown on $\delta^2\text{H} - \delta^{18}\text{O}$ and $\delta^{18}\text{O}$ time-series (2000–2005) diagrams. The water-isotope framework comprises the Global Meteoric Water Line (GMWL: $\delta^2\text{H} = 8 \delta^{18}\text{O} + 10$) as defined by Craig (1961), the LMWL: $\delta^2\text{H} = 6.7 \delta^{18}\text{O} - 19.2$ from precipitation collected at Fort Smith, Northwest Territories (Canadian Network for Isotopes in Precipitation (CNIP); <http://www.science.uwaterloo.ca/~twdedwar/cnip/cniphome.html>), and the (LEL: $\delta^2\text{H} = 4.2 \delta^{18}\text{O} - 68.5$) calculated using approaches described in Wolfe *et al.* (2007b). Local rainfall and snow collected during years 2000–2005 and analysed for $\delta^2\text{H}$ and $\delta^{18}\text{O}$ show excellent agreement with the Fort Smith LMWL ($\delta^2\text{H} = 6.9 \delta^{18}\text{O} - 21.2$; Falcone, 2007). Other parameters shown include: ice-free season precipitation (δ_{Ps} ; Gibson and Edwards, 2002), local amount-weighted annual precipitation (δ_{P} ; Fort Smith CNIP station), winter precipitation (δ_{PW} assuming ~41% total annual precipitation falls as snow from Environment Canada Weather Station at Fort Chipewyan, Alberta), a terminal lake in isotopic and hydrologic steady-state fed by mean annual precipitation (δ_{SS} ; Wolfe *et al.*, 2007b) and the theoretical limiting isotope enrichment attainable by a desiccating water body under average ice-free season conditions (δ^* ; Wolfe *et al.*, 2007b).

flood event on the lake water balance. Overall, PAD 31 exhibits hydrological conditions typical of restricted-drainage basins (Table I).

Although fewer lake water samples were obtained from PAD 39, isotope values are strongly variable, spanning a large segment of the LEL (Figure 4(c)). Like PAD 23, input of river floodwater was not observed over the 5-year monitoring period and, as expected, all PAD 39 lake water values are more isotopically-enriched than Athabasca River values due to evaporative enrichment. In contrast to PAD 23, however, most water samples plot above the LEL indicating the substantive role of rainfall on the lake water balance. As described in Wolfe *et al.* (2007b), rainfall-influenced basins such as PAD 39 (Table I) are very shallow, located near the large open-drainage lakes that occupy the central portion of the delta, and are likely prone to extensive or complete desiccation during the ice-free season. While no observational evidence can confirm desiccation during the monitoring period, strong evaporative isotope enrichment approaching average ice-free season δ^* in 2001 and enrichment beyond δ_{SS} in 2002 and 2004 (years of highly variable precipitation—Figure 2(a), (b), and (d)) attest to the strong sensitivity of the basin's water balance to local atmospheric conditions. Notably, results from both PAD 39 and PAD 23 indicate that even in the absence of input from river water, contemporary climatic conditions have not resulted in desiccation within our 5-year sampling interval because of the contributions from snowmelt and rainfall. Several consecutive 2001-like climate years would, however, undoubtedly lead to rapid water-level drawdown of PAD 39 and other basins whose water balance is dominated by summer precipitation, and complete desiccation of these basins perhaps within a decade as others have suggested (PADPG, 1973; Peters *et al.*, 2006a).

Lake-sediment chronologies

Total ^{210}Pb activity profiles for PAD 23, PAD 31, and PAD 39 decline exponentially with increasing sediment depth but all display downcore variability, as expected in an active fluvial-deltaic depositional environment subject to fluctuating sedimentation rates (Figure 5). Of the three basins, the core from PAD 23 shows the lowest deviation from a pattern of exponential decline of total ^{210}Pb activity. Background (i.e. supported) ^{210}Pb levels (0.032 Bq/g) are obtained at a sediment depth of 33.25 cm, substantially deeper than for the sediment cores from the other basins, indicating higher sedimentation rates at PAD 23 (Figure 5(a)). The basal CRS-modelled ^{210}Pb date of 1877 (33.25 cm) results in a mean sampling resolution of 2.6 years from 0 to 33.25 cm depth, with uncertainties (± 2 SD units) ranging from ± 0.1 to 0.9 years (average = ± 0.2 years).

In comparison, supported ^{210}Pb levels (0.027 Bq/g) were obtained at a much shallower depth of 13.75 cm in the PAD 31 core, reflecting slower sedimentation rates in this basin (Figure 5(b)). An exponential increase in

^{210}Pb activities from 13.75 to 6.25 cm indicates relatively constant sedimentation rates between those stratigraphic levels, but a dilution of ^{210}Pb activities between 5.75 and 2.25 cm is likely due to particularly high sedimentation rates during this interval. Employing the CRS model produces a basal ^{210}Pb date of 1882 (13.75 cm) and a mean sampling resolution of 4.3 years from 0 to 13.75 cm depth. Uncertainties (± 2 SD units) range from ± 0.2 to 2.3 years (average = ± 0.6 years).

For PAD 39, fluctuations in the exponentially declining ^{210}Pb activity profile are also indicative of changes in sedimentation rates (Figure 5(c)). Supported ^{210}Pb levels (0.028 Bq/g) are obtained at a depth of 20.75 cm providing a basal CRS-modelled ^{210}Pb date of 1859 (20.75 cm) and a mean sampling resolution of 3.5 years from 0 to 20.75 cm depth. Uncertainties (± 2 SD units) range from ± 0.1 to 8.4 years (average = ± 0.8 years).

Hydroecological reconstructions

Profiles depicting 20th century changes in geochemical and biological multi-proxy data measured from the gravity cores obtained from PAD 23, PAD 31, and PAD 39 are shown in Figure 6 and include cellulose-inferred lake water $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_{\text{lw}}$) values, organic carbon content, summed totals of the percent abundance of closed- (or *Cocconeis placentula var euglypta*) and open-drainage indicator diatom taxa, algal pigment β -carotene concentration and key-plant macrofossils. These stratigraphic records have been selected from a large array of analyses conducted (Hall *et al.*, 2004), and include indicators proven to be most sensitive to hydroecological change in shallow lakes in this ecosystem (e.g. Edwards *et al.*, 2004; Wolfe *et al.*, 2005). Also shown are stratigraphic horizons associated with the two recent geomorphic events that have altered the flow of the Athabasca River and its tributaries (the Athabasca River cutoff in 1972 and the Embarras Breakthrough in 1982; Figure 3) to highlight evidence for directional hydroecological responses as revealed by the multi-proxy paleolimnological records described below.

At PAD 23, low $\delta^{18}\text{O}_{\text{lw}}$ values of similar composition to present-day Athabasca River water $\delta^{18}\text{O}$ values and near-equal proportions of diatoms indicative of closed- and open-drainage conditions reflect the frequent input of river floodwaters prior to ~ 1970 (Figure 6(a)). *Fragilaria* diatom taxa tolerant of turbid waters and low light availability, as typically occurs in open-drainage basins in the absence of abundant macrophyte microhabitats, are of particularly high relative abundance between ~ 1900 and 1970 (Hall *et al.*, 2004). Organic carbon content and β -carotene (total algal abundance) concentration are low until ~ 1975 and ~ 1980 , respectively, consistent with reduced light availability associated with the increase in detrital input and minerogenic turbidity from river flooding. At ~ 1940 , there is a sharp increase in concentration of leaves of *Drepanocladus* and other aquatic mosses as well as more frequent occurrence of *Carex* (sedge) seeds. Aquatic mosses likely grew at the margins of the lake, which was probably somewhat larger

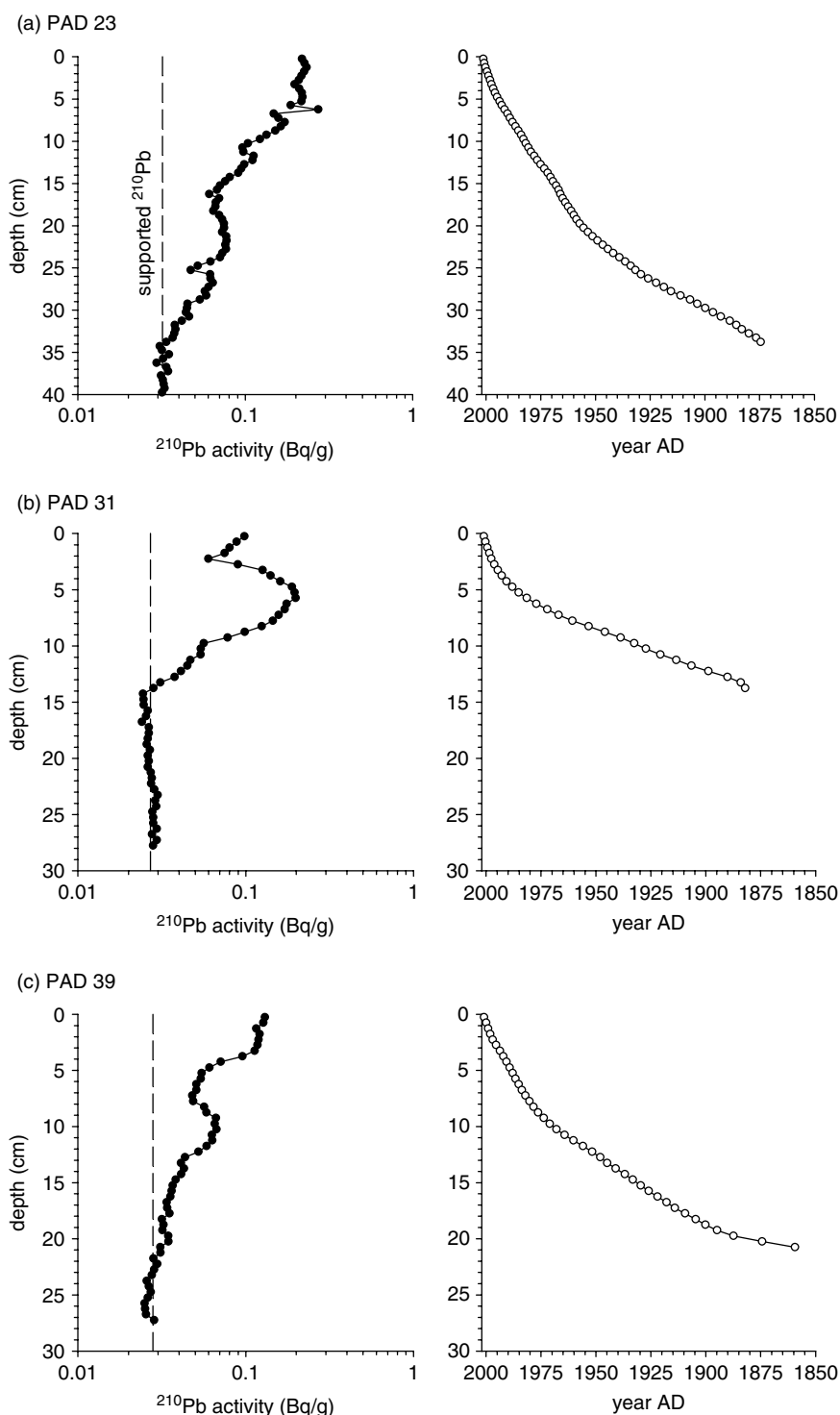


Figure 5. ^{210}Pb activity and depth-age profiles for sediment cores from (a) PAD 23, (b) PAD 31 and (c) PAD 39.

than at present. After ~ 1970 , increased $\delta^{18}\text{O}_{\text{lw}}$ values suggest greater importance of evaporation to the lake water balance, increased organic carbon content and β -carotene concentration signal an increase in aquatic production, higher abundance of closed-drainage indicator diatoms suggests reduced river influence and increased abundance of *Sphagnum* leaves record the development of floating *Sphagnum* (moss) beds that currently flank much of the lake's margin. Together, these data indicate

evolution towards reduced influence of river floodwaters and declining water levels over the past ~ 30 years at PAD 23. These results and the timing of prominent stratigraphic changes in all proxy records coincide with the construction of the Athabasca River Cut-Off in 1972, which straightened the course of the Athabasca River, increased the local channel gradient and reduced the connection between the Athabasca River and distributary channels leading to PAD 23 (as indicated in Figure 3(a) and (b)).

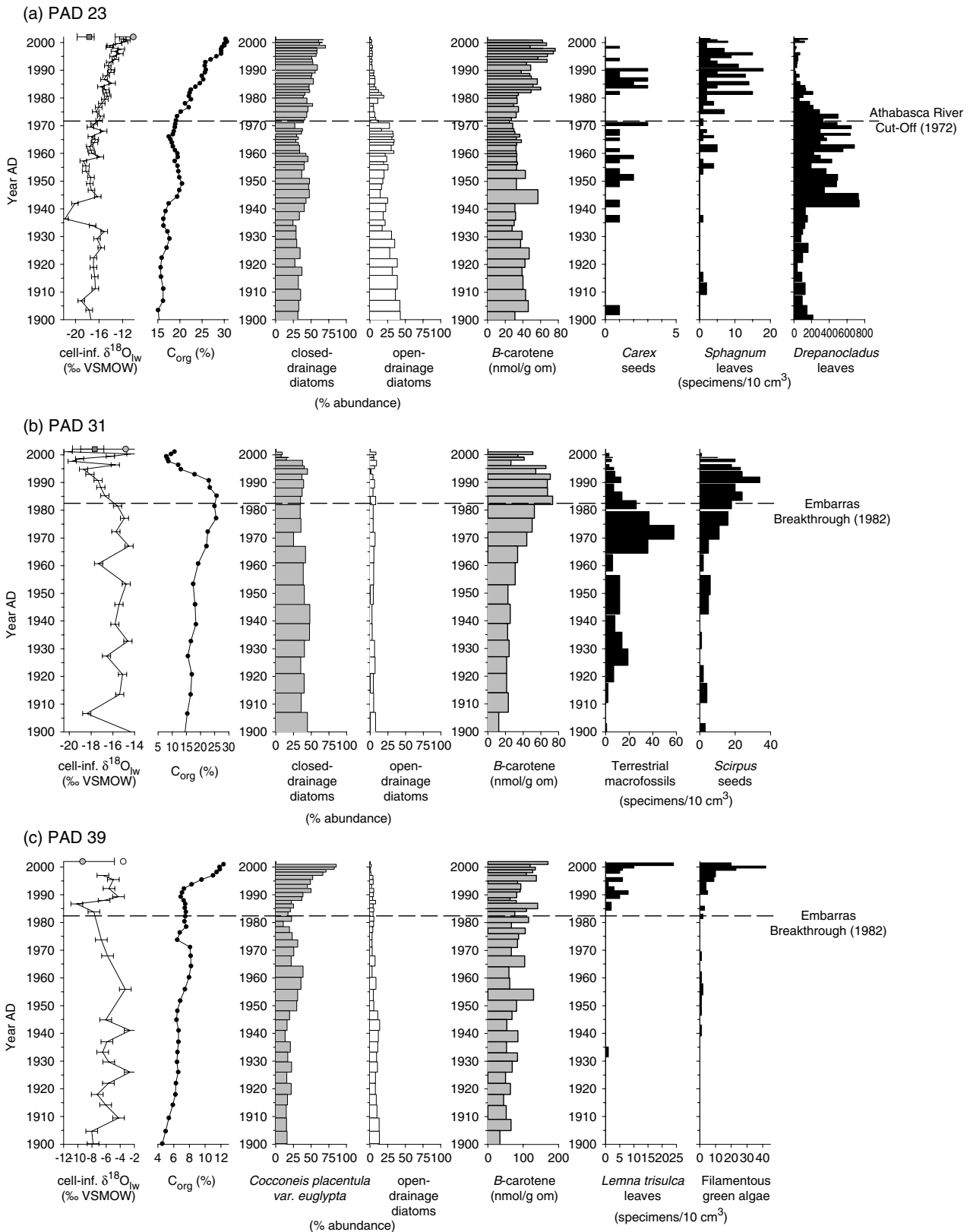


Figure 6. A summary of key multi-proxy paleolimnological records for (a) PAD 23, (b) PAD 31 and (c) PAD 39 plotted versus year AD from age models in Figure 5. Also shown in the cellulose-inferred lake water $\delta^{18}\text{O}$ plots are 5-year ranges and averages of Athabasca River water $\delta^{18}\text{O}$ [shaded squares in (a) and (b)] and lake water $\delta^{18}\text{O}$ [shaded circles in (a)–(c)], as well as the limiting isotopic enrichment [open circle in (c)] from Figure 4. Excellent agreement between uppermost cell-inf. $\delta^{18}\text{O}_{\text{lw}}$ and measured lake water $\delta^{18}\text{O}$ confirms an aquatic origin of the cellulose organic fraction, further supported by low C/N ratios downcore (Hall *et al.*, 2004) and correspondence to other indicators. Some samples for PAD 39 contained insufficient cellulose for oxygen-isotope analysis.

From ~1900 to ~1980, most $\delta^{18}\text{O}_{\text{lw}}$ values in the sediment core from PAD 31 are higher relative to present-day Athabasca River water $\delta^{18}\text{O}$ values, indicating the important role of evaporation on water balance with moderate influence from river flooding (Figure 6(b)). Organic carbon content, β -carotene concentration, terrestrial plant macrofossil concentration (mainly comprising shoreline herbs such as *Chenopodium*, *Rumex*, *Rorippa*, and *Potentilla palustris*; Hall *et al.*, 2004) and *Scirpus* seed concentration are also low over most of this interval, consistent with low aquatic production and/or elevated detrital input associated with periodic river flooding. Values of these paleolimnological indicators, however, begin to increase to ~1970 suggesting reduced river flooding. Even more pronounced changes begin to occur after ~1980, with a rapid decline and subsequently more variable $\delta^{18}\text{O}_{\text{lw}}$ values consistent with an increase in the magnitude and frequency of river flooding. Terrestrial plant macrofossils also register a sudden decline at this horizon while organic content and β -carotene concentration remains high, likely reflecting lake deepening and stimulation of algal growth during the initial phase of increased river input. *Scirpus* continues to increase, also consistent with higher or seasonally variable water levels. The past ~5–10 years may very well be the period of strongest and most persistent river flooding during the past century, based on highly variable $\delta^{18}\text{O}_{\text{lw}}$ values, decline in organic carbon content and β -carotene concentration, and decrease in the abundance of diatoms indicative of closed-drainage conditions. The earliest evidence of this most recent increase in flood frequency at PAD 31 is closely correlated with the Embarras Breakthrough in 1982 and the resultant increase in Embarras River flow through Cree and Mamawi creeks towards the lake (Figure 3(c) and (d)).

Much higher $\delta^{18}\text{O}_{\text{lw}}$ values at PAD 39 (Figure 6(c)) compared to both the PAD 23 and PAD 31 $\delta^{18}\text{O}_{\text{lw}}$ records indicate strong evaporative conditions with values approaching the limiting lake water isotopic enrichment, δ^* , based on average ice-free season climatic conditions (Figure 4). The presence of low abundance of open-drainage indicator diatoms, however, suggests that periodic river influence has likely been critical to the maintenance of water in this lake over the past 100 years. In these records, the most striking stratigraphic change occurs at ~1990, marked by increases in $\delta^{18}\text{O}_{\text{lw}}$ values, organic carbon content, β -carotene concentration, *C. placentula* var. *euglypta* (an epiphytic diatom species associated with closed-drainage conditions; Hall *et al.*, 2004), *Lemna trisulca* leaves and filamentous green algae. Taken together, these patterns suggest more productive conditions and reduced river influence arising from the Embarras Breakthrough, which channelled flow towards PAD 31 and Mamawi Lake in the central portion of the PAD and away from the north-eastern sector of the Athabasca Delta where PAD 39 is located (Figure 1). Evidently, the most striking stratigraphic changes in both PAD 39 and PAD 31 are after ~1985 indicating that it took several years before the most pronounced hydroecological effects

of the Embarras Breakthrough occurred, consistent with measured increases in the distribution of Breakthrough flow relative to Embarras flow from 1982 to 1986 (De Boer *et al.*, 1994).

DISCUSSION

Five years of isotopic monitoring has revealed the relative importance of river floodwater, snowmelt, rainfall, and evaporation controls on the lake water balances of PAD 23, PAD 31, and PAD 39, three hydrologically distinctive basins in the Athabasca Delta (Figure 4; Table I). PAD 23, a closed-drainage basin, is dominated by precipitation input sources including both snowmelt and rainfall, and characterized by a lake water balance, which tends to approach steady-state conditions by mid to late summer as water is lost via evaporation. In contrast, PAD 31 is a restricted-drainage basin, with input derived mainly from river floodwaters that may enter the basin during the spring thaw when ice jams develop on the Athabasca River and its distributaries, or as a result of high discharge events during the ice-free season. While evaporation (and outflow during high-water stages) results in water loss, river floodwater inputs have been sufficiently frequent to maintain a positive water balance in this basin throughout the period of monitoring. Similar to PAD 23, PAD 39 is controlled primarily by input from precipitation and evaporative loss, but source waters tend to be dominated by rainfall.

Analysis of multi-proxy paleolimnological records suggests that the contemporary hydrological regimes of these basins are the outcome of very recent geomorphic changes that have altered the flow of the Athabasca River and its distributaries in the delta (Figure 6). The engineered Athabasca River Cut-Off in 1972 is coincident with a trend towards more evaporative and productive conditions at PAD 23, based on an increase in $\delta^{18}\text{O}_{\text{lw}}$ values, organic carbon content, and β -carotene concentration, as well as higher abundance of closed-drainage indicator diatoms. The subsequent natural development of the Embarras Breakthrough in 1982 and increased flow through Cree and Mamawi creeks has had the opposite effect on PAD 31, indicated by a rapid decline and more variable $\delta^{18}\text{O}_{\text{lw}}$ values, decrease in terrestrial plant macrofossils, and with associated changes to the lake water nutrient balance and aquatic ecology that are consistent with more frequent inundation of river floodwaters. Divergence of Athabasca and Embarras river flow towards the central low-lying sector of the PAD has led to a predictable response downstream along the main channel stems, as revealed by increases in $\delta^{18}\text{O}_{\text{lw}}$ values, organic carbon content, β -carotene concentration, epiphytic diatom abundance, *L. trisulca* leaves, and filamentous green algae at PAD 39 reflecting higher aquatic production and a decline in river influence. On the basis of the temporal perspectives provided by the paleolimnological records, these directional hydroecological changes over the past ~10–30 years are the most profound to have occurred during the 20th century.

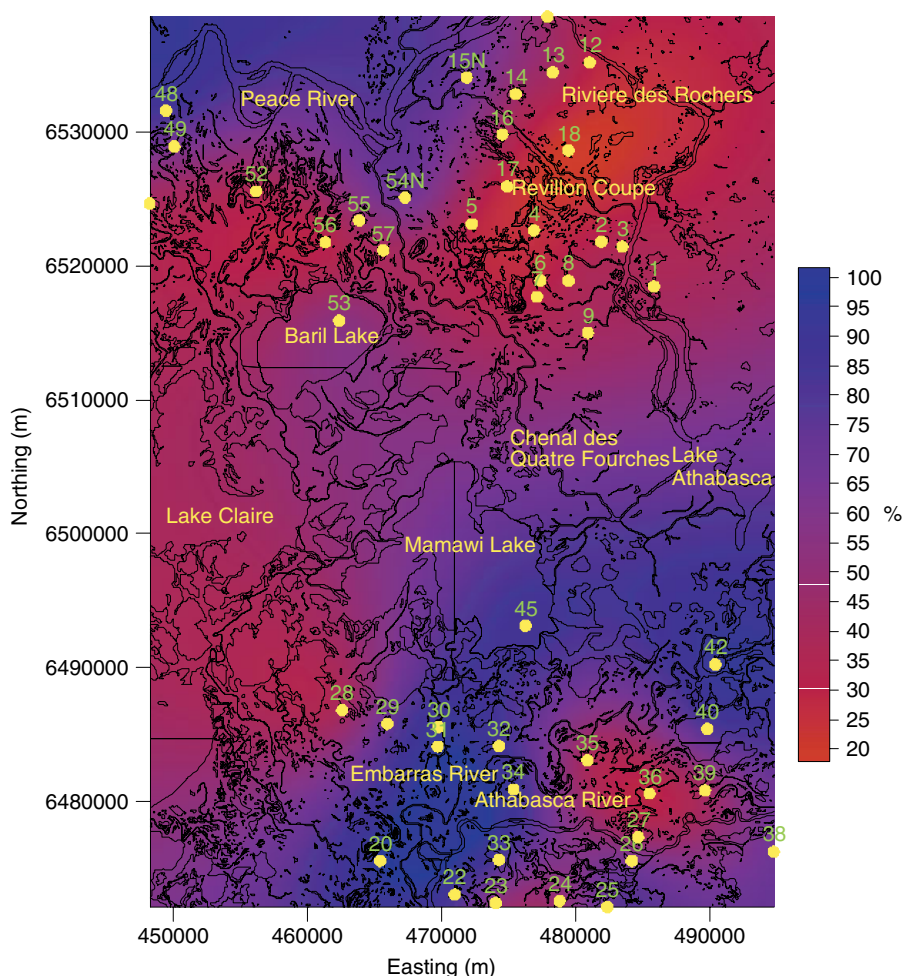


Figure 8. Estimated lake water replenishment, expressed as a percent of total lake volume, during May 2003 based on an isotopic two-component mixing model and supported by total suspended sediment data and field observations (Falcone, 2007). Landscape expression of these results is derived from radial basis function interpolation with multiquadratic basis kernel type. Blue areas capture regions that received primarily river floodwaters whereas red areas contain basins that received exclusively snowmelt. Widespread flooding occurred in the Athabasca Delta because of ice jams that developed on the Athabasca and Embarras rivers. Limited ice-jam flooding also occurred along the Peace River in the north-west.

in May 2003 following the largest ice-jam flood event to have occurred in the Athabasca Delta since we began our monitoring in 2000. Values were calculated using a simple two-component mixing model, incorporating measurements of pre- and post-event lake water oxygen-isotope composition, snowmelt oxygen-isotope composition, and river water oxygen-isotope composition, and are supported by total suspended sediment data and field observations (Falcone, 2007). The south-west–north-east blue swath through the Athabasca Delta in Figure 8 encompasses basins that received large volumes of primarily river water as a result of flooding, whereas the red zone in the south-east includes basins that were not flooded but instead received comparatively lesser volumes of snowmelt during the spring thaw. PAD 31 was flooded during this event while PAD 23 and PAD 39 were not. These results are entirely consistent with recent trends in the paleolimnological records from these basins and are driven, to a large extent, by geomorphic change and altered flow patterns of the Athabasca River. Thus, the 2003 flood event may indeed be reflective of the typical, contemporary spatial distribution of river floodwaters

resulting from ice jams that periodically develop on the Athabasca River and its distributaries. Altered Athabasca River flow resulting from the Athabasca River Cut-Off has likely led to reduced flooding elsewhere in the vicinity of PAD 23 (e.g. basin 24 in Figure 8), which is also the most elevated portion of the Athabasca Delta (Peters *et al.*, 2006b). Similarly, other basins near PAD 39 (e.g. basins 26, 27, 35, and 36 in Figure 8) along the Embarras and Athabasca rivers downstream of the Embarras Breakthrough have also probably become less susceptible to river flooding. Importantly, these results suggest that the red zone depicted in the south-eastern portion of Figure 8 are areas in the Athabasca Delta most hydroecologically sensitive to continued drying given recent trends in climate and Athabasca River discharge.

CONCLUSIONS AND IMPLICATIONS

Integration of water-isotope monitoring and multi-proxy paleolimnological records has identified that recent geomorphic changes have strongly influenced contemporary hydroecological conditions of the Athabasca Delta. The

Athabasca River Cut-Off, an excavated channel constructed in 1972 to prevent an avulsion of the Athabasca River into the Embarras River, has reduced the frequency of ice-jam floods entering nearby PAD 23. The Embarras Breakthrough, a natural flow diversion through Cree and Mamawi creeks that occurred in 1982, has increased the frequency of river floodwater inundating PAD 31 to the north and decreased the flood susceptibility of PAD 39 downstream along the main channel stem of the Athabasca and Embarras rivers to the north-east. Trends of increasing evaporation at PAD 23 and PAD 39 over the past ~30 and ~20 years, respectively, are likely being enhanced by declining relative humidity, increasing temperature and possibly by decreasing Athabasca River discharge, whereas geomorphic-induced hydroecological change at PAD 31 has overwhelmed effects caused by these other potential drivers. Directional hydroecological change at all three basins appears to be representative of local landscapes within the Athabasca Delta based on corresponding spatial distribution of river floodwaters during a major ice-jam flood event in 2003.

Our studies conclude that the hydroecology of the Athabasca sector of the PAD is far more sensitive to changes (be they natural or anthropogenic) in Athabasca River flow than the north-eastern Peace sector, which appears to be remarkably resilient to apparent changes in Peace River flow regimes. For example, a multi-proxy paleolimnological record from Spruce Island Lake indicates the basin has retained water for over 200 years in spite of its distal location from major flood distributaries of the Peace River and wide range of flood frequency over this time period (Wolfe *et al.*, 2005, 2006b). Water has likely remained in this basin because the nature of its catchment, bordered on three sides by forested bedrock, provides sufficient snowmelt run-off to offset the effects of evaporation. Snow captured in the undulating landscape of the Peace sector with its many bedrock outcrops provides a more important source of run-off to basins than previously recognized (Falcone, 2007). On the other hand, we suspect that the very flat terrain of the Athabasca sector is less effective in generating snowmelt run-off to counteract evaporation in the absence of river flooding over extended periods of time. Given the likelihood of continued climatic and Athabasca River discharge trends, and with discharge potentially subject to accelerate change from increased industrial pressures along the river's downstream reaches (Schindler and Donahue, 2006; Schindler and Smol, 2006), recent drying at PAD 23, PAD 39 and the surrounding landscape may represent the leading edge of rapidly evolving hydroecological conditions in the Athabasca Delta. Implications of these results include reduction in aquatic habitats and, if such trends were to continue, complete loss due to lake desiccation.

Knowledge gained from contemporary and paleoenvironmental studies has substantially improved our understanding of hydroecological variability and change, and their causes, in a complex deltaic environment under the

protection of international conventions but facing multiple stressors that threaten its ecological integrity. Results from these studies have been especially effective for deciphering the relative roles of local (e.g. geomorphic events) versus regional (e.g. climate and river discharge) drivers of hydroecological change, as is required for informed stewardship. A particularly important outcome with direct application to water resource policy development is that parts of the Athabasca Delta have undergone drying over the past 2–3 decades, largely due to geomorphic changes in river flow, and these areas are most susceptible to terrestrialization given expected climatic and hydrological trajectories. The multiple approaches we have applied to characterize temporal and spatial hydroecological variability at a landscape scale may indeed represent a way forward in knowledge generation for balancing ecosystem and economic water resource demands, as others have suggested recently (e.g. Hannah *et al.*, 2007), and are readily transferable to other large, freshwater ecosystems.

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