Impacts of climate and river flooding on the hydro-ecology of a floodplain basin, Peace-Athabasca Delta, Canada since A.D. 1700

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Abstract

Multi-proxy paleolimnological analyses on lake sediment cores from “Spruce Island Lake” (58° 50.82′ N, 111° 28.84′ W), a perched basin in the northern Peace sector of the Peace-Athabasca Delta (PAD), Canada, give insights into the relative roles of flow regulation of the Peace River and climatic variability on the basin hydro-ecology. Results indicate substantial variability in basin hydro-ecology over the past 300 years ranging from seasonal to periodic desiccation in the 1700s to markedly wetter conditions during the early 1800s to early 1900s. The reconstruction is consistent with (1) dry climatic conditions that defined the peak of the Little Ice Age and subsequent amelioration evident in conventional ring-width and isotopic analyses of tree-ring records located hydrologically and climatically upstream of the PAD, and (2) Peace River flood history inferred from sub-annual magnetic susceptibility measurements from another lake sediment record in the Peace sector of the PAD. Although regulation of the Peace River for hydroelectric power generation since 1968 has long been considered a major stressor of the PAD ecosystem leading to reduced frequency of ice-jam and open-water flooding and an extended period of drying, our results show that current hydro-ecological status is not unprecedented as both wetter and drier conditions have persisted for decades in the recent past under natural climatic variability. Furthermore, paleolimnological evidence from Spruce Island Lake indicates that recently observed dryness is part of a longer trend which began some 20–40 years prior to Peace River regulation.

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Introduction

The Peace-Athabasca Delta (PAD), situated at the confluence of the Peace and Athabasca rivers at the western end of Lake Athabasca in northern Alberta, Canada, is one of the world’s largest freshwater deltas. Numerous shallow basins characterize the PAD and support bountiful wildlife, including migratory waterfowl and a large population of North American bison. The PAD has been designated a Ramsar site (International Ramsar Convention on Wetlands) and is part of Canada’s largest national park, Wood Buffalo National Park.

We are conducting extensive multidisciplinary research to gain better understanding of the past and present hydrology, ecology, and climate of the PAD (Wolfe et al., 2002). This manuscript is one of several from a comprehensive, multidisciplinary, three-year research program reported in Hall et al. (2004), which included multi-proxy paleolimnological reconstructions spanning the past few hundred years from several basins in the PAD. The aim of our research is to assess the impacts of both natural and anthropogenic factors, ranging from climatic variability and change to the influence of river flow regulation resulting...
from hydroelectric power generation at the headwaters of the Peace River since 1968. The latter is of particular interest because of the possibility that alteration of Peace River discharge may be affecting 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). Concerns became particularly acute in the early 1990s as an extended dry period that followed a major flood in 1974 had resulted in extremely low water levels in many perched basins, which provide important wildlife habitat (Prowse and Conly, 1998). Although many environmental studies have been conducted in the PAD over the past 35 years to address ecological impacts of low water levels (PADPG, 1973; PADIC, 1987; PADTS, 1996; Gummer et al., 2000), absence of long-term hydrological and ecological records has limited the ability to objectively evaluate the importance of anthropogenic versus natural climatic forcing in regulating hydro-ecological conditions of the PAD.

Our paleoenvironmental studies have included multi-century reconstructions of regional climatic variability near the headwaters of the Athabasca River (located climatically and hydrologically upstream from the PAD) and Peace River flood history in the northern part of the PAD (Hall et al., 2004; Wolfe et al., 2005a). The climate records, which consist of quantitative reconstruction of changes in temperature and relative humidity, were developed from carbon and oxygen isotope analyses of a composite tree-ring chronology. These records clearly depict cold and very dry conditions during the 1700s corresponding to the peak of the Little Ice Age. Subsequent warming and moistening occurred until the early part of the 20th century, followed by progressive drying. Reconstruction of flood history, inferred from exceptionally high-resolution (sub-annual) magnetic susceptibility measurements on a sediment core from an oxbow lake adjacent to a major flood distributary of the Peace River, shows close correspondence with the isotope-based climate records. In particular, the dry 1700s were characterized by extremely low flood frequency.

Here, we focus on a sub-decadal, 300-year, multi-proxy hydro-ecological record from a perched (i.e., closed-drainage) basin informally named “Spruce Island Lake.” Located in the relict fluvial-deltaic landscape of the northern Peace sector of the PAD, it is distant from major flood distributaries of the Peace River and outside the effect of all but the most extreme floods. Hence, Spruce Island Lake was expected to be very sensitive to former arid conditions that occurred during the Little Ice Age. The paleohydrological record is based on quantitative reconstruction of lake water balance derived from analysis of cellulose oxygen isotope composition constrained by investigations of modern isotope hydrology. Organic carbon and nitrogen content, diatom assemblages, and plant macrofossils, the latter two techniques founded on a delta-wide surface-sediment assessment of biological proxy indicators (Hall et al., 2004), are used to further refine paleohydrological inferences as well as provide information pertaining to related ecological changes. We compare the Spruce Island Lake paleolimnological record with likely major hydro-ecological drivers, namely regional climatic variability and Peace River flood history (Hall et al., 2004; Wolfe et al., 2005a), to address the following research questions: (1) Have hydro-ecological conditions in Spruce Island Lake since 1968 varied beyond the range of natural variation during the past 300 years? (2) Is there evidence that flow regulation of the Peace River has caused significant changes in hydro-ecological conditions in Spruce Island Lake? (3) How is hydro-ecological variability at Spruce Island Lake related to natural climatic variability and Peace River flood history?

Our study demonstrates that profound changes in hydro-ecological conditions are clearly a natural feature of this ecosystem, independent of human influence or intervention. Such temporal insight is critical for understanding the hydro-ecological evolution of the PAD, anticipating future hydro-ecological trajectories under continuing climatic variability as well as the likelihood of increasing demand for hydroelectric power and consumptive water use (e.g., Athabasca tar sands oil extraction), and developing effective and appropriate water resource management strategies.

Study area

Climatic and hydrological setting of the Peace-Athabasca Delta

The Peace-Athabasca Delta (Fig. 1) is centered at approximately 59°N 112°W within the subhumid midboreal ecoclimatic region (Ecoregions Working Group, 1989) and is characterized by long, cold winters and relatively short, warm summers. Based on 1971–2000 climate normals (Environment Canada weather station at Fort Chipewyan, Alberta), 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. Precipitation averages 391.7 mm annually, with about 59% falling as rain during the May–September period. Mean annual lake evaporation calculated from class-A pan measurements at Fort Smith, NWT, 145 km to the north, is 525 mm (AES, 1993).

Under normal flow conditions, Lake Athabasca, a major inland waterbody in western Canada, drains 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 which enters Great Slave Lake to the north (Fig. 1). During high-water events on the Peace River, accentuated by ice-jam conditions near the confluence of the Peace and Slave rivers, water can flow southwards from the Peace River through these channels and cause overland flooding of the northern Peace sector of the PAD. Periodic ice-jam flooding is thought to be important for maintaining...
the water balance of many perched basins in the Peace sector of the PAD, as high Peace River discharge during the open-water season is generally insufficient to cause widespread flooding (Prowse and Lalonde, 1996). The last major spring ice-jam floods of the northern Peace sector occurred in 1996 and 1997.
Lake water sample collection and isotope analyses

Field and laboratory methods

Lake water sample collection and isotope analyses

Water samples were collected at ~10-cm water depth from the central part of Spruce Island Lake several times between October 2000 and September 2003 to examine modern variability in hydrology 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 as δ-values, representing deviations in per mil (‰) from Vienna Standard Mean Ocean Water (VSMOW) such that \( \delta = \left( \frac{R_{\text{sample}}}{R_{\text{VSMOW}}} - 1 \right) \times 10^3 \), where R is the \(^{18}O/^{16}O\) or \(^2H/H\) ratio in sample and VSMOW. Results of \( \delta^{18}O \) and \( \delta^2H \) analyses are 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 \( \delta^{18}O \) and ±2.0‰ for \( \delta^2H \).

Site description—“Spruce Island Lake”

“Spruce Island Lake” (informal name; 58° 50.82‘ N, 111° 28.84‘ W; 209.9 m asl) is a small (~22.5 ha), shallow (\( Z_{\text{max}} = 0.9 \) m), isolated, upland lake in a bedrock basin, located between the Chenal des Quatre Fourches and the Revillon Coupé (Fig. 1). The lake is surrounded on three sides by mature forest on bedrock outcrops, with a possible inlet/outlet via lower-lying ground to the north during high water stages. Consistent with limnological conditions of other hydrologically closed basins in the PAD (Hall et al., 2004; Wolfe et al., 2005b), Spruce Island Lake is nutrient rich, relatively alkaline (Table 1) and supports extensive growth of colonial filamentous algae and submerged aquatic macrophytes including Potamogeton spp. and Chara spp. Emergent vegetation including Sparganium eurycarpum, Acorus calamus, Alisma plantago-aquatica, and Typha latifolia is restricted to shallow coves between the bedrock outcrops that define most of the shoreline.

Field and laboratory methods

Table 1

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Lake sediment coring and analyses

Collection of lake sediment cores

Three sediment cores (33–36 cm long) were collected near the center of Spruce Island Lake in June 2001 using a modified KB gravity corer (Glew, 1989), sectioned into 0.5-cm intervals (Glew, 1988) at the field station, and subsequently analyzed as briefly described below. Longer sediment sequences were obtained with a 10-cm diameter Russian peat corer but have not yet been subsampled or analyzed. Replicate short cores were collected to provide sufficient material for multi-proxy paleolimnological analyses, including organic carbon and nitrogen elemental content and cellulose oxygen isotope composition (KB-2: 35.0 cm in length), radiometric dating and diatom analyses (KB-3: 36.0 cm), and plant macrofossil analyses (KB-4: 33.0 cm). Loss-on-ignition analyses were determined on all KB sediment cores. Additional analyses of textural parameters, mineralogical components, carbon and nitrogen isotope composition, and pigments were conducted but are not reported because these proxies are less sensitive tools for tracking hydro-ecological changes in this particular basin.

Core chronology

Samples from KB-3 were analyzed for \(^{210}Pb\) at the Environmental Radiochemistry Laboratory, Department of Fisheries and Oceans, Winnipeg, Manitoba. One- to 3-g samples of dry sediment were analyzed 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 (Oldfield and Appleby, 1984), which assumes a constant flux of \(^{210}Pb\) to the sediment and changing sedimentation rates, was used to establish the geochronology of core KB-3. The resulting age-depth profile was applied to cores KB-2 and KB-4 based on matching stratigraphic changes in loss-on-ignition (LOI) and further constrained by peaks in the abundance of the diatom Fragilaria pinnata.

Moisture and loss-on-ignition determinations

Samples for moisture content, organic matter content, and total carbonate content were evaluated for all cores at 0.5-cm intervals by weight loss on heating to temperatures of 85°C, 500°C, and 1000°C, respectively (Dean, 1974; Heiri et al., 2001). Organic matter and total carbonate content are expressed as percent of the dry sediment weight.
Organic carbon and nitrogen content and cellulose oxygen isotope analyses

Samples from KB-2 were analyzed for cellulose oxygen isotope composition following procedures detailed in Wolfe et al. (2001b). Initially, all sub-samples were pre-treated with 10% (by volume) HCl at 60°C to remove carbonate. This was followed by rinsing with de-ionized water, freeze-drying, and sieving to remove coarse debris using a 500-μm sieve. Organic carbon and nitrogen content were measured on subsamples of the fine fraction by an elemental analyzer. Further treatment, involving solvent extraction, bleaching, and alkaline hydrolysis, was conducted to remove non-cellulose organic constituents. This was followed by hydroxylamine leaching to remove iron and manganese oxyhydroxides, and heavy-liquid density separation using sodium polytungstate to concentrate the cellulose fraction, the latter based on procedural refinements (Wolfe et al., 2004). Cellulose oxygen isotope composition was measured by a continuous flow-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 2O, also as described above (−55.5‰; Coplen, 1996). Analytical uncertainty, based on sample duplicates, is ±0.51‰.

Diatom analyses

Samples from KB-3 were prepared by acid digestion following standard methods (Hall and Smol, 1996). Diatom valves were identified and counted (~400 per sample) at 1000× magnification using a Zeiss Axioskop Iplus light microscope fitted with differential interference optics (numerical aperture = 1.30). Taxonomic references for diatom identification include Foged (1981), Kammer and Lange-Bertalot (1986–1991) and Cumming et al. (1995).

Plant macrofossil analyses

Samples of wet sediment (5 cm³) from KB-4 were washed through a 125-μm mesh screen with warm tap water. Material retained on the sieve was sorted in water using a binocular dissecting microscope at 8–40× magnification, and all identifiable macro-remains were counted. Identifications were made with the aid of modern reference specimens and keys including Bertsch (1941), Martin and Barkley (1961), Berggren (1969, 1981), Montgomery (1977), and Artjuschenko (1990).

Results and interpretation

Contemporary isotope hydrology

Local precipitation and surface waters are generally characterized by two variably well-defined linear trends in δ18O–δ2H space. Precipitation falls on or close to the Global Meteoric Water Line (GMWL), whereas surface waters that have undergone evaporation generally plot in a linear cluster to the right of the GMWL along a slope generally in the range 4 to 6. The trajectory of the Local Evaporation Line (LEL) and the rate and extent of isotopic enrichment in the residual liquid phase during evaporation are controlled by local atmospheric conditions during the thaw season (Craig and Gordon, 1965). In the region of the PAD, the predicted LEL based on available isotopic and climatic data is defined by δ2H = 4.26δ18O-68.5 (Fig. 2a; see Wolfe et al., 2005b). Key points along the predicted LEL include the mean isotopic composition of amount-weighted annual precipitation (δp), the isotopic composition of a terminal lake fed by δp in hydrologic and isotopic steady state (δss), and the limiting isotopic composition of a desiccating lake under average thaw season climatic conditions (δ*).

Results of O and H isotope analyses of Spruce Island Lake water collected over three years (October 2000 to September 2003) span a broad range of values (~8‰ in δ18O; ~35‰ in δ2H), reflecting strong sensitivity to seasonal hydrological variability and, more specifically, the opposing effects of evaporative enrichment and dilution by precipitation (Figs. 2b,c). Data are localized about the predicted LEL indicating that the lake captures annual precipitation close to δp in composition and that pre-existing isotopic and climatic information provides a useful semi-quantitative framework for assessing instantaneous water balance conditions from Spruce Island Lake at times of sampling. Hence, clustering of several samples collected between the months of June and October beyond δss indicates pronounced non-steady-state evaporation (i.e., net evaporative loss). Extreme enrichment approaching δ* was captured in August 2001, reflecting particularly dry conditions that summer, whereas late summer rain events evidently curtailed the effects of evaporative isotopic enrichment during summer 2002. Further lowering of lake water isotopic composition due to input of isotopically depleted snowmelt is indicated by samples obtained in early spring 2003. Prolonged effects of substantial snowmelt input to Spruce Island Lake during spring 2003 may also be reflected by subsequent evaporative enrichment that just exceeds δss, a result consistent with considerably greater snowfall at Fort Chipewyan AB in winter 2002–03, compared to winters of 2000–01 and 2001–02 (data available from Environment Canada: http://climate.weatheroffice.ec.gc.ca/climateData/monthlyData_e.html). Overall, results suggest that in the absence of input from river flooding, which has not occurred since at least 1997, Spruce Island Lake and its catchment capture sufficient precipitation and runoff under modern climatic conditions to maintain standing water in the basin. This is in contrast to water-balance measurements from other perched basins in the Peace sector by the Peace-Athabasca Delta Project Group (PADPG, 1973), who concluded that perched basins ~1 m deep or less could dry up within two years without replenishment by river flood inputs.
Hydro-ecological reconstruction

Sediment core chronologies

Chronologies for the sediment cores are based on $^{210}$Pb analysis of core KB-3 (Figs. 3a,b). Total $^{210}$Pb activity generally declines exponentially with depth reaching supported $^{210}$Pb levels (0.034 Bq/g) at 19.25 cm. The resulting basal CRS modeled $^{210}$Pb date is 1855 and provides a mean sampling resolution of 3.9 years from 0 to 19.0 cm. Errors (±2SD units) of the CRS modeled $^{210}$Pb dates range from ±0.2 to ±3.4 years (average = ±0.9 years). Extrapolation of dates below the level of unsupported $^{210}$Pb activity, based on linear regression of the CRS modeled $^{210}$Pb dates, results in a basal date of 1716 for the KB-2 core. Chronological sequencing of the other cores, based on matching stratigraphic changes in LOI and a peak in Fragilaria pinnata, provides basal extrapolated dates of 1708 and 1752 for the KB-2 and KB-4 cores, respectively (Fig. 3c). Note that direct application of CRS-modeled dates from the KB-3 core by depth would have provided an older date of 1724 for the KB-2 core, and a slightly younger date of 1740 for the KB-4 core but based on the good correspondence of changes in proxy indicators described below, the adjusted chronologies based on matching LOI and Fragilaria peaks appear to provide more reasonable chronologies for these cores.
Oxygen isotope stratigraphy and water balance reconstruction

Analysis of the oxygen isotope composition of sediment cellulose, a proxy for lake water $\delta^{18}O$ (Wolfe et al., 2001b), reveals substantial paleohydrological variability over the past 300 years at Spruce Island Lake (Fig. 4a). Overall, raw cellulose-inferred lake water $\delta^{18}O$ values range from about -14 to -1% and are in close agreement with the range of several measured samples of lake water $\delta^{18}O$ collected from 2000 to 2003. Particularly, good agreement exists between estimated average lake water $\delta^{18}O$ from samples spanning 3 yrs and the uppermost cellulose-inferred lake water $\delta^{18}O$ from the sediment core, strongly supporting the use of sediment cellulose as a tracer of lake water oxygen isotope history. According to the smoothed profile generated by a three-point running mean, cellulose-inferred lake water $\delta^{18}O$ values are at their highest from the early 1700s to ~1780, with values averaging about -5% and which exceed the
estimated $\delta_{ss}$ value based on modern climatic and isotopic information. A brief shift to low cellulose-inferred lake water $\delta^{18}O$ values ($\sim -10\%$) occurs between ~1780 and ~1800 before a return to moderately high values slightly greater than contemporary $\delta_{ss}$ ($\sim -7\%$) of similar duration between ~1800 and ~1820. After ~1820, cellulose-inferred lake water $\delta^{18}O$ values decline attaining a minimum at ~1880 ($\sim -12\%$), which is then followed by oscillations (approximately decadal) superimposed on a gradual increase to the present values that are close to $\delta_{ss}$ ($\sim -8\%$).

Interpretation of sediment-inferred lake water $\delta^{18}O$ records requires separating changes related to the isotopic composition of source water, reflecting the integrated signature of surface and subsurface inflow and precipitation, from changing hydrological factors (often primarily evaporative enrichment) that may subsequently modify the isotopic content of the lake water (Edwards et al., 2004). For Spruce Island Lake, a closed-drainage lake, changes in water balance due to local hydroclimatic factors (i.e., precipitation + catchment runoff − evaporation), as well as the input of high-magnitude floods from the Peace River, are likely the predominant controls on lake water $\delta^{18}O$ fluctuations. This hypothesis is supported by measurements of modern lake water $\delta^{18}O$ from 2000 to 2003, which fluctuate along the LEL, and can be ascribed semi-quantitatively to changes in water balance driven by evaporative loss countered by precipitation dilution because the lake has not received flood water from nearby rivers since at least 1997 (Fig. 2b). Furthermore, decadal reconstruction of precipitation $\delta^{18}O$ from the Athabasca tree-ring record shows changes that are generally $< \pm 3\%$ over the past 300 years (Hall et al., 2004). Hence, the $>10\%$ range in cellulose-inferred lake water $\delta^{18}O$ values in the Spruce Island Lake sediment core are unlikely to have been strongly influenced by changes in the isotopic composition of precipitation.

The cellulose-inferred lake water $\delta^{18}O$ record from Spruce Island Lake can be quantified readily into a history of changing water balance, assuming that (1) water balance is the predominant signal recorded in the lake sediments, as discussed above, and (2) evaporative isotopic enrichment has occurred under conditions of hydrologic steady-state, which appears to be largely the case except for the period ~1710 to ~1780. Water balance can be conveniently expressed in terms of an evaporation-to-inflow ($E/I$) ratio (Fig. 4b) using isotope-mass balance equations and the
linear resistance model of Craig and Gordon (1965), defined as:

$$E/I = \left[\frac{1 - h + 10^{-3}e_K}{h - 10^{-3}e}\right] \times \left[\frac{\delta_L - \delta}{\delta^* - \delta_L}\right]$$

where $h$ is the atmospheric relative humidity normalized to the saturation vapour pressure at the temperature of the air–water interface, $e^*$ and $e_K$ represent the respective equilibrium and kinetic effects, expressed as per mil (‰) separations between the liquid and vapour phases, $\delta = e^* + e_K$, $\delta_L$ is the isotope composition of lake water, $\delta_1$ is the weighted-mean isotopic composition of input waters to a catchment, $\delta^* = (\delta_\lambda + e^*) / (h - 10^{-3}e)$ where $\delta^*$ is the limiting isotopic enrichment attainable when a water body evaporates to near-zero volume, and $\delta_\lambda$ is the isotope composition of atmospheric moisture (Gibson and Edwards, 2002; Edwards et al., 2004). This model has frequently been applied to assess contemporary water balances of lakes approximating hydrologic steady-state (e.g., Gibson, 2001), and increasingly for quantitative reconstructions of paleohumidity and paleo-water balance from lake sediment oxygen isotope records (e.g., Edwards et al., 1996; Wei and Gasse, 1999; Wolfe et al., 2001a).

Using modern estimates of evaporation-flux-weighted $h$ (68.2%), $T$ (12.3°C), $\delta_\lambda$ (−25.4‰), and $\delta_1 = \delta_p$ (−18.8‰) derived from Canadian climate normals and pre-existing isotope hydroclimate as a first approximation, model results indicate that strongly negative water balances ($I < E$) characterized the ~1710–1780 interval, whereas positive steady-state water balances ($I > E$) have dominated for most of the past 230 years (Fig. 4b). Exceptions to the latter include a brief interval between ~1800 and ~1820 when Spruce Island Lake also experienced persistent non-steady-state net evaporation ($I < E$), and recent decade- to multi-decade-long intervals (1940–1950; 1965–1985) including the past few years in which the lake appears to have been, on average, close to hydrological balance ($I/E$) approximating hydrologic steady-state (e.g., Gibson, 2001), and is commonly observed in lacustrine stratigraphies (Tyson, 1995). This is followed by a decline in $C_{org}$ and N values to ~1870 (~15%, ~1.5%) and a subsequent rise to ~1930 (~20%, ~2.0%). $C_{org}$ and N values are relatively stable until ~1980, after which they increase to the top of the core (~22%, ~2.6%). In contrast, weight C/N ratios narrowly range from ~8 to 11 (Fig. 4d), ratios characteristic of organic matter derived from aquatic sources (Meyers and Lallier-Vergès, 1999). C/N ratios are slightly higher from ~1700 to 1830 (~10.5) after which a gradual decline (~10.5 to 8) occurs to the top of the core.

In the highly productive shallow lakes and wetlands of the PAD, organic matter content stored in stratigraphic records reflects a complex interplay of several fluxes. These are dominated by in-lake production and sedimentation of aquatic macrophytes and phytoplankton, respiration and re-utilization of dissolved organic matter in the water column and sediment, and dilution by high suspended loads of inorganic detrital material supplied by periodic floods. Broad correspondence with major features of the isotope-inferred $E/I$ record (Fig. 4b), however, suggests that hydrological status may strongly influence changes in the organic matter stratigraphy from Spruce Island Lake. For instance, exceptionally dry conditions during the 1700s correspond to low organic content, probably reflecting low productivity or more likely, reduced organic matter preservation. The latter explanation is consistent with preferential loss of labile N-bearing compounds, which may account for the slightly higher C/N ratios during this interval. As wetter conditions developed by the end of the 1700s, a corresponding increase in organic content may signal an increase in productivity and/or preservation, which evidently peaked during the second, less intense drying phase between ~1800 and ~1820. Parallel trends towards lower isotope-inferred $E/I$ ratios and declining organic content from the early to mid-1800s are likely due to increased influx of inorganic sediment (possibly accompanied by reduced productivity) associated with an increase in river water input. Subsequent increase in isotope-inferred $E/I$ ratios and organic content after ~1870 to ~1930 likely represents a reduction in river water input and an increase in productivity. Stable percentages of organic content from ~1940 to ~1980 are consistent with generally closed-basin steady-state hydrological conditions. We interpret increases in organic content in near-surface sediments to reflect incomplete diagenesis of organic material. A corresponding decline in C/N ratios indicates that labile N-bearing compounds may only be preserved in the uppermost sediments, as is commonly observed in lacustrine stratigraphies (Tyson, 1995).

**Diatom stratigraphy**

Of the 150 diatom taxa identified in the Spruce Island Lake sediments, 24 taxa were common in the assemblages...
with relative abundances greater than 5% (Fig. 5). The common taxa are mostly epiphytic forms (e.g., *Achnanthes minutissima*, *Gomphonema angustum*, *Cocconeis placentula*, and *Nitzschia amphibia*) and the small, benthic *Fragilaria pinnata*, which were well represented in the surficial sediments of 57 shallow aquatic basins of the PAD (Hall et al., 2004). Planktonic taxa, most likely originating from river waters (Karst-Riddoch et al., unpublished data), include *Cyclotella* spp., *Fragilaria crotonensis*, and *Aulacoseira ambigu*. These occur in relatively low abundance, representing a maximum of only 7% of diatom assemblages. The predominance of epiphytic and benthic taxa in the sedimentary diatom assemblages suggest that Spruce Island Lake has been shallow and has supported extensive macrophyte communities for most of the past ~300 years (Fig. 5). Major preservational and/or compositional changes in the diatom record occur at ~1790, 1850, and 1950 reflecting hydrological and limnological changes at Spruce Island Lake, based on observed relationships between modern sedimentary diatom assemblages, hydrological conditions, and limnological properties of aquatic basins in the PAD (Hall et al., 2004).

Prior to ~1790, diatom preservation is very poor, with evidence of dissolution on many of the valves and a lack of sufficiently preserved valves for confident diatom counts between ~1725 and 1750 (Fig. 5). Dissolution of diatom valves is consistent with very shallow, alkaline waters (Barker et al., 1994) and may be indicative of periodic desiccation. Diatom dissolution was also evident in the surface sediments of several of the most shallow (less than 50 cm deep) basins in the PAD that exhibited relatively high alkalinity and high concentrations of Ca and Mg, presumably due to evaporative concentration of cations under dry conditions and their remobilization into the water column following rain events (Hall et al., 2004). Under such highly alkaline conditions, preservation of siliceous algal remains is likely hindered due to the ionic dissociation of silicic acid at elevated pH values (Barker et al., 1994). Further support for dry conditions is provided by high E/I ratios indicative of non-steady-state net evaporation as reconstructed from the cellulose-inferred lake water δ¹⁸O profile (Fig. 4b).

River water likely became a major source of water for Spruce Island Lake beginning at ~1790 based on the large increase in *Fragilaria pinnata* from less than 10% abundance prior to ~1790 to more than 40% by ~1820 and the concurrent decrease in the previously dominant epiphytic diatom, *Achnanthes minutissima*. Similarly high percent abundances of *F. pinnata* were only observed in the surface sediments of turbid, open-drainage basins of the PAD with direct connection to the river channel network (Hall et al., 2004). Sustained, direct inflow of turbid river waters into Spruce Island Lake resulting in low-light conditions likely favored the proliferation of the low-light tolerant *F. pinnata*, and reduced submerged aquatic plants that provide habitat for epiphytic diatom taxa. In addition to

![Figure 5. Relative abundance profiles of the dominant diatom taxa (with relative abundances of ≥5% in at least one sediment interval) from core KB-3. The hatched bar indicates sediment interval with poor diatom preservation due to dissolution.](image-url)
the above compositional changes in the diatom assemblages, diatom preservation improves markedly at ~1790, providing further evidence of wetter conditions at Spruce Island Lake, the timing of which is closely correlated with a major shift to low isotope-inferred E/I ratios (Fig. 4b). Wetter conditions and hence reduced evaporative concentration of alkalinity-generating ions would likely have alleviated problems with silica dissolution previously attributed to the extremely dry conditions during the early- and mid-1700s. Moreover, silica availability may have been enhanced with inputs of silica-rich river waters (Hall et al., 2004; Wolfe et al., 2005b).

An abrupt change to more restricted-drainage conditions occurs at ~1850 with the sharp decline of *F. pinnata* to abundances of less than 10% (Fig. 5). From ~1850–1950, epiphytic taxa (e.g., *A. minutissima*, *Cocconeis placentula*) common in clear-water, macrophyte-rich, restricted- and closed-drainage basins in the PAD (Hall et al., 2004) gradually regain dominance, indicating a trend towards reduced river influence relative to that of the preceding wet interval (~1790–1850) and increased abundance of submerged macrophyte habitat. However, continued presence of *F. pinnata* and several planktonic centric taxa associated with river water (Hall et al., 2004) suggests periodic river inputs during the period ~1850–1950. A progression to increasingly closed-drainage conditions, which presently characterize Spruce Island Lake, began ~1950 with the disappearance of *F. pinnata* and riverborne planktonic centric diatoms.

**Plant and invertebrate macrofossil stratigraphy**

Plant macrofossil assemblages in core KB-4 are dominated by remains of *Chara* spp., which are present in all samples (Fig. 6). Other submerged aquatic macrophytes, including *Myriophyllum* spp. and several species of *Potamogeton*, occur throughout most of the core. *Daphnia* ephippia and ostracod valves were also recorded in most samples. Continuous presence of submerged macrophytes, as well as aquatic invertebrates, indicates the existence of a shallow aquatic environment for at least part of the growing season throughout the past ~250 years. This is supported by our surface-sediment study in which *Chara* and *Myriophyllum* remains were found exclusively in closed- and restricted drainage basins with at least 50 cm of water (Hall et al., 2004).

Overall, marked stratigraphic changes are less evident in the macrofossil profile compared to the other multi-proxy records discussed above. The lone exception is the pronounced change at ~1800, characterized mainly by a shift in the abundance of *Chara* stems, filamentous green algae, and ostracod valves (Fig. 6). *Chara* stems and filamentous green algae are present in most samples between ~1750 and 1800, but occur only sporadically after ~1800, whereas ostracod valves become more abundant after ~1800. High abundance of *Chara* stems and filamentous green algae prior to ~1800 is exceeded only by concentrations at the top of the core. The latter is not unusual for near-surface sediments in similar shallow lakes (Hall et al., 2004) and is likely attributable to the short period of decomposition since the sediments were
deposited. However, delicate macro-remains such as these do not appear to be commonly preserved in deeper sediments. Their almost consistent presence in moderate abundances during the ~1750–1800 period may indicate high production of these two types of algae, rapid burial due to high sedimentation rates, or slow decomposition. The latter two possibilities, however, appear to be inconsistent with evidence for very shallow waters and poor organic matter preservation based on the multi-proxy data discussed above (Figs. 4,5). On the other hand, low ostracod abundance prior to ~1800 likely indicates low water levels for at least part of the year. Alternatively, a dense cover of *Chara* spp. and filamentous algae may also have resulted in relatively reduced habitat availability for some ostracod species.

After ~1810, ostracod valves are more abundant than in the 1700s and, conversely, *Chara* spp. and filamentous algae are less abundant (Fig. 6), presumably related to generally higher water levels as inferred from the other proxy records (Figs. 4,5). Exceptions include a single sample at ~1850, which contained no ostracod valves likely due to very high minerogenic turbidity from increased river input as suggested by the other proxy records, and higher abundance of *Chara* spp. and filamentous algae in freshly deposited sediment at the top of the core.

**Discussion**

Multi-proxy evidence from sediments of Spruce Island Lake indicates the hydro-ecological conditions varied substantially over the past 300 years characterized by multi-decadal dry and wet periods (Fig. 7). For example, the driest period occurred during most of the 1700s, as shown by high isotope-inferred E/I ratios indicative of persistent non-steady-state net evaporation and dominance of epiphytic, closed-drainage indicator diatom taxa. Although plant macrofossil data suggest sufficient water was available during at least a portion of the growing season to support aquatic macrophytes, low concentrations and poor preservation of diatoms, low organic content due to poor preservation, and low ostracod abundance strongly suggests very shallow water depth or that the lake underwent periodic to seasonal desiccation at this time. This is further substantiated by crumbly sediment observed at this same depth interval in a 1-m-long intact core retrieved using a Russian peat corer, which could indicate effects of sediment freezing during low water stands or dessication from ~1700 to 1780, (2) mainly open- to restricted-drainage hydrological status that was strongly to variably influenced by turbid river-derived flood water from ~1780 to 1940, and (3) near closed-basin steady-state conditions associated with clear, macrophyte-dominated water from ~1940 to present.

Comparison to independent records of climatic variability and Peace River flood history indicate that these are, indeed, likely major drivers of hydro-ecological history reconstructed from Spruce Island Lake sediments (Fig. 7). As described earlier, reconstruction of relative humidity and mean annual temperature variability, derived from carbon and oxygen isotope analyses of a composite tree-ring record from the headwaters of the Athabasca River, indicates cold and very dry conditions during the 1700s (Hall et al., 2004; Fig. 7). Warmer and wetter conditions developed in the early 1800s through to the early 1900s, followed by drier conditions since ~1925. This climate record is strongly consistent with the peak of the Little Ice Age (LIA) corresponding to the relatively cold 1700s and early 1800s, followed by post-LIA climatic amelioration, and is in close agreement with the three-phase Spruce Island Lake hydro-ecological reconstruction. Notably, tree-ring based precipitation records for the Banff–Jasper–Foothills area also show the LIA as a period of persistent dryness bracketed by precipitation maxima around 1530–1550 and 1890–1910 (Luckman and Watson, 1999; Watson and Luckman, 2001), and recent re-analysis of Northern Hemisphere tree-ring records by Esper et al. (2002) has resolved a sequence of long-term temperature changes strongly consistent with the isotopic-inferred climate history.

Downstream in the PAD, these records of climatic variability are also strongly expressed in reconstructed Peace River flood history, which also shows close correspondence with the Spruce Island Lake three-phase hydro-ecological record (Fig. 7). For example, high-resolution analyses of magnetic susceptibility from an oxbow lake adjacent to a major flood distributary of the Peace River suggests exceptionally low flood frequency during the cold and dry 1700s (Hall et al., 2004; Wolfe et al., 2005a) and is consistent with extremely dry conditions at Spruce Island Lake during this period. An inferred increase in relative humidity during the early 1800s to the early 1900s...
Figure 7. Athabasca River headwater climate quantified from isotope dendroclimatological analyses (Hall et al., 2004), Peace River flood frequency from lake sediment magnetic susceptibility measurements (Hall et al., 2004; Wolfe et al., 2005a), and summary of key paleolimnological indicators at Spruce Island Lake. Hatched zone indicates poor diatom preservation. Also shown is photograph of the corresponding sediment core interval obtained using a Russian peat corer. Note the crumbly structure in the lower portion of image. Climate records are based on carbon and oxygen isotope analyses on cellulose extracted from a decadal averaged tree-ring record from the eastern Rocky Mountains (Fig. 1), and utilizing a coupled response surface method to deconvolve changing moisture (expressed as relative humidity, Δh) and temperature (ΔT) signals (Edwards et al., 1999, 2000; Jiang et al., 2000). Peace River flood record is based on sub-annual analyses of magnetic susceptibility on a sediment core obtained from an oxbow lake adjacent to the Revillon Coupé (PAD 15; Fig. 1). Increases in magnetic susceptibility correspond with increased detrital influx from the Revillon Coupé, which are associated with flood events (Hall et al., 2004; Wolfe et al., 2005a). Both raw data and 5-year running mean profiles are shown. Dashed vertical lines represent estimates of lake basin sill threshold and the 1974 flood threshold values, respectively. The 1974 flood event caused widespread flooding of the Peace sector of the PAD (Pietroniro et al., 1999). Dashed horizontal lines indicate approximate timings of major hydro-ecological changes, as described in the text.
correlates with variable flood frequency and generally wet conditions at Spruce Island Lake (Fig. 7). A subsequent trend to lower relative humidity since the early- to mid-1900s corresponds with reduced flood frequency and a shift to drier conditions at Spruce Island Lake.

Conclusions and implications for water resource management

High-resolution (i.e., sub-decadal) stratigraphic analysis of cellulose oxygen isotope composition coupled with a multi-year time-series of lake water isotope composition provides an exceptionally robust framework for quantitative reconstruction of past water balance history. Comparison with other geochemical and biological proxy data strongly supports and further refines the paleohydrological reconstruction, while also contributing additional insight into aspects of nutrient balance and, in particular, changes in aquatic ecology. This study clearly demonstrates that in complex depositional environments such as the PAD, a multi-proxy paleolimnological approach can effectively inform water resource management issues that are at the interface of hydrology and ecology, as summarized below with respect to research questions outlined in the Introduction.

(1) Have hydro-ecological conditions in Spruce Island Lake since 1968 varied beyond the range of natural variation during the past 300 years?

Multi-proxy paleolimnological data from Spruce Island Lake indicate that sub-decadal-averaged hydro-ecological conditions after regulation of the Peace River began in 1968 are well within the broad range of natural variability observed over the past ~300 years. For instance, both markedly wetter and drier conditions compared to recent decades have occurred at Spruce Island Lake over this time period.

(2) Is there evidence that flow regulation of the Peace River has caused significant changes in hydro-ecological conditions in Spruce Island Lake?

Although concerns have focussed on observed drying since the Peace River has been regulated in 1968, paleolimnological evidence from Spruce Island Lake indicates this to be part of an extended period of drying that was initiated in the early to mid-1900s. Resolving whether significant river regulation impacts are superimposed upon natural climate-driven hydrological variability over this time interval, however, remains uncertain and further research on developing and integrating independent quantitative local paleoclimate records are required to partition the relative roles of these factors (cf. Hall et al., 1999). This information is also needed to generate future projections of perched basin water balances under climate change and variability scenarios and continued river regulation, which is ultimately necessary for effective multi-stakeholder environmental stewardship of the PAD.

(3) How is hydro-ecological variability at Spruce Island Lake related to natural climatic variability and Peace River flood frequency?

Multiple lines of evidence indicate standing water has persisted in Spruce Island Lake for at least the past ~200 years. This period spans several multi-decadal intervals without a major Peace River ice-jam flood (Fig. 7; Hall et al., 2004), including a recent 21-year period (1975–1995) that post-dates river regulation. Evidently, Spruce Island Lake has received sufficient direct precipitation and catchment runoff to offset evaporative loss at times of infrequent flooding during the past ~200 years. This clearly underscores the important roles of local climate and catchment attributes in maintaining lake water balance and hydro-ecology, as is also shown by our three-year time series of water isotope data. Based on our analyses, only during the exceptionally dry climate that prevailed during the peak of the Little Ice Age has Spruce Island Lake undergone possible seasonal to periodic desiccation. Nonetheless, our records illustrate that Peace River flood frequency is also a principal driver of longer term (i.e., decadal-scale) variability in perched basin water balance history in the Peace sector of the PAD extending well beyond the recent record (Prowse and Lalonde, 1996; Prowse and Conly, 1998, 2000) to at least the past ~300 years.

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