Developing temporal hydroecological perspectives to inform stewardship of a northern floodplain landscape subject to multiple stressors: paleolimnological investigations of the Peace–Athabasca Delta

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Abstract: Effective stewardship of ecologically-significant floodplain landscapes requires knowledge of the relative roles of natural processes and upstream human activities on environmental flows. In these landscapes, hydroecological conditions that develop from potentially competing drivers, such as climate change and industrial development, tend to be expressed at spatial and temporal scales that are often inadequately captured by existing monitoring datasets. Consequently, perceived cause–effect relations may be misunderstood, conflict can escalate among stakeholders, and effectiveness of surveillance systems, policies, and governance may be impaired. This is the context for the Peace–Athabasca Delta (PAD), an internationally-recognized water-rich floodplain landscape located in northern Alberta (Canada) that has been subject to multiple stressors. Here we synthesize evidence from paleolimnological records that have fostered an unparalleled window into the natural history of this landscape. Over the past 12 years, we have assembled numerous decadal- to multicentennial-long records of hydrological and ecological variability, including an exceptionally detailed chronicle of Peace River flood frequency and magnitude spanning ~600 years. These efforts recently culminated in a 5200-year reconstruction of Lake Athabasca water-level history. Results have provided the foundation to identify drivers of landscape change and generate insight into the delta’s dynamic and ongoing evolution. Contrary to widespread perceptions that hydroelectric regulation of the Peace River since the late 1960s has reduced the frequency of ice-jam floods and lowered floodplain lake-water levels, results indicate that climate variability exerts the overwhelming influence on the delivery of water to the PAD. We show that impending climate-driven freshwater scarcity of a scale unprecedented in our collective societal memory now poses a significant threat to the ecological integrity of this world-renowned landscape and a major challenge to water resource managers. Also, we propose a hydroecological monitoring program, built upon the knowledge gained from our extensive process studies and paleoenvironmental research, to inform effective ongoing stewardship of the delta.

Key words: floodplain landscapes, ecosystem stewardship, water resource management, environmental flows, climate change, hydroecology, paleolimnology, Peace–Athabasca Delta.

Résumé : Une gestion efficace des données écologiquement significatives concernant les paysages de plaines inondables nécessite une connaissance des rôles relatifs des processus naturels et des activités humaines en amont, sur les flux environnementaux. Les conditions hydroécologiques se développant dans ces paysages à partir d’agents potentiellement compétitifs comme le changement climatique et le développement industriel, ont tendance à s’exprimer à des échelles spatio-temporelles souvent inadéquatement prises en compte par le suivi actuel des ensembles de données. Conséquemment, les relations de cause à effet perçues peuvent être mal comprises pourraient se traduire par une escalade des conflits entre parties prenantes, ce qui pourrait nuire à l’efficacité des systèmes de suivi ainsi qu’aux politiques et à la gouvernance. C’est le contexte que l’on retrouve dans le Delta Peace–Athabasca (DPA), un paysage internationalement reconnu pour les eaux riches de sa plaine d’inondation, localisé dans le Nord de l’Alberta (Canada) et déjà soumis à de multiples agents stressants. Les auteurs présentent une synthèse des preuves obtenues provenant de données paléolimnologique ayant ouvert une fenêtre sans pareil...
Introduction

It ain’t what you don’t know that gets you into trouble. It’s what you know for sure that just ain’t so. [Mark Twain]

Natural and anthropogenic alterations to river-flow regimes can have marked effects on downstream floodplain ecosystems and, in particular, the hydrological, limnological, and ecological conditions that are critical for supporting biologically productive aquatic habitats (Junk 2005; Wiklund et al. 2012a). Ensuring “environmental flows” (i.e., maintenance of sufficient water to support downstream environmental, social, and economic needs [Dyson et al. 2003]) in the face of climate change, urbanization, agricultural demand, industrial development, and other stressors is a global issue that presents significant challenges to water resource managers (WWAP 2012). These challenges commonly stem from difficulties deciphering the relative roles of multiple drivers of ecosystem change, which must be identified to link cause and effect accurately. If the key drivers of change are not correctly determined, misguided remedial action and policy decisions can arise, and conflict can escalate among stakeholders in attempts to secure water resources while maintaining downstream aquatic ecosystem integrity. At a more fundamental level, we contend that insufficient knowledge of hydroecological variability of stressed floodplain ecosystems over space and time is at the heart of these matters, knowledge that is rarely available even where routine ecosystem-monitoring programs are in place.

These are the circumstances that have transpired at the Peace–Athabasca Delta (PAD), Canada, the world’s largest freshwater boreal delta (Fig. 1). The PAD, a 6,000 km² water-rich productive landscape of shallow lakes, wetlands, and meadows, is located where flow from the Peace and Athabasca rivers converges in northeastern Alberta. An oasis for birds that migrate along North America’s four major flyways and home to the world’s largest free-roaming herd of bison, the PAD was protected in 1922 with the creation of Wood Buffalo National Park — Canada’s largest national park and one of Canada’s 15 UNESCO World Heritage Sites. The delta also has strong socio-cultural significance to the Mikisew Cree and Athabasca Chipewyan First Nations and Métis, who now reside in Fort Chipewyan on the shore of Lake Athabasca. Fort Chipewyan is a village of nearly 1000 people, and it is Alberta’s oldest community (est. 1788). In 1982, the PAD was designated as a Ramsar Wetland of International Importance in recognition of its ecological, historical, and cultural value.

Despite national and international efforts to preserve this northern freshwater landscape, the PAD has been the focus of intense scrutiny for more than 40 years because of the perceived negative effects of the WAC Bennett Dam, which was constructed >1000 km upstream of the PAD near the headwaters of the Peace River in 1968 to generate hydroelectricity. Concerns over the potential linkage between regulation of the Peace River and the ecological integrity of the PAD developed in the late 1960s, beginning with low levels on Lake Athabasca that coincided with the 1968–1971 filling of the hydroelectric reservoir, Williston Lake (British Columbia). This promptly led to the 18-month-long Peace–Athabasca Delta Project Group study supported by the governments of Canada, Alberta, and Saskatchewan — a $1.5 million environmental impact assessment of Peace River regulation on the delta landscape (PADPG 1972, 1973), and subsequently the Peace–Athabasca Delta Technical Studies (1993–96) which aimed to “understand available options and select the most suitable remediation strategy for restoring the role of water in the delta” (PADTS 1996, pp. 1–2).

Deltas change naturally over time. They are amongst the most complex of environments on Earth because they exist in a terrestrial-aquatic transitional zone and change dynamically as a result of the interplay of processes on land, in the air, and water. The Peace–Athabasca Delta is no exception. Yet, until recently, little was known about how this landscape has evolved or how it has responded to climate change — two critical knowledge gaps that have long hampered efforts to disentangle effects of river regulation from those caused by natural processes.

In 2000, in response to multimillion dollar lawsuits launched by the First Nation communities of Fort Chipewyan against the British Columbia Hydro and Power Authority and the Government of Canada, we began an investigation into...
the natural history of the delta to address a question that, in spite of over 30 years of study, had yet to be clearly answered: Has the WAC Bennett Dam caused discernible, directional changes to the hydrology and ecology of the delta? To answer this question required detailed knowledge of conditions in the delta before the dam was constructed and how those conditions have varied over time in response to natural forces. Our approach was to couple extensive field-based hydroecological process studies with techniques in the field of paleolimnology — the multidisciplinary science that uses the physical, chemical, and biological information preserved in lake sediments to reconstruct past environmental conditions (Smol 2008).

While the early phases of our research were focused largely on generating empirical data to address the question stated above, attention eventually shifted — more broadly and more importantly — to identify shifting patterns in freshwater availability that have critical implications for societies and ecosystems throughout western North America. In short, our findings have failed to implicate flow regulation by the dam in causing discernible, directional changes in the hydrology and ecology of the delta, but they have revealed a far greater concern for those living in watersheds that rely on freshwater supplied by rivers that drain the eastern slopes of the Canadian Rocky Mountains. Indeed, the status of these freshwater resources is at a crossroads. At a time when consumption of water in these drainage basins is increasing, we must now prepare to deal with potential, climate-driven water-supply reductions in the region well beyond the magnitude and duration known to our collective societal memory.

Here we highlight and synthesize our key findings from over a decade of intensive research in the PAD. In the process, we illustrate the essential need for developing hydroecological perspectives of sufficient temporal and spatial scales to lay the foundation for informed multistakeholder decision-making. We offer lessons learned that may assist others charged with the stewardship of floodplain ecosystems, and watersheds in general, stressed by multiple drivers. Finally, we identify key implications of our research and provide recommendations for water resource management of the PAD. We acknowledge that several reviews have previously been published on hydrological research in the PAD, most notably those affiliated with the Peace–Athabasca Delta Technical Studies (PADTS) as well as the Northern River Basins Study and subsequent Northern River Ecosystems Initiative (PADTS 1996; Prowse et al. 2002, 2006; Prowse and Conly

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**Fig. 1.** Location of the Peace–Athabasca Delta (PAD), Alberta, Canada. Identified sites are locations of paleolimnological records in the PAD (PAD 5, 9, 12, 15, 23, 31, 39, 54) and on Bustard Island (North Pond [BINP]) in western Lake Athabasca.
Prior paleoenvironmental studies in the Peace–Athabasca Delta

Prior to the initiation of our paleolimnological investigations of the PAD, two notable studies had been conducted to examine long-term patterns of hydrological variability. Instead, recognition that a paleohydrological perspective was required to identify drivers of ecosystem change came very soon after the WAC Bennett Dam was constructed. Unfortunately, the findings of these studies have not been particularly well-recognized in subsequent PAD-related literature, yet they reveal evidence of marked natural hydrological variability inherent in this landscape that is consistent with results from our paleolimnological studies.

The 1971–1973 Peace–Athabasca Delta Project Group (PADPG) study focused on conducting detailed investigations into what was perceived to be a problem of low water levels on Lake Athabasca, and the effects on the delta and local First Nation communities. The main priority of the Project was to develop an immediate solution to restore water levels and identify a long-term solution to the anticipated low water levels that were predicted to persist in years to come. At that time, Lake Athabasca was considered to play a critical role in annual flooding of the delta and the replenishment of shallow, perched (i.e., closed- and restricted-drainage) basins that offered abundant shoreline habitat for migratory waterfowl, muskrats, and other wildlife. This belief was based on the notion (now known to be incorrect — see below) that for about 20 days in the early summer, the Peace River rises higher than the level of Lake Athabasca, hydraulically damming Lake Athabasca outflow, thereby diverting waters through the Lake Mamawi – Lake Claire system to flood the entire delta (PADPG 1972). During the filling of the Williston Reservoir (1968–1971), instrumental records indicated that summer water levels in Lake Athabasca declined by ~1 m compared with the long-term average (1934–1967; Kellerhals 1971) and flooding of the delta did not occur. Coincidentally, perched basin shoreline in the PAD was reduced by ~36% and water surface area by ~38%, and exposed 500 km² of mudflats, which became rapidly occupied by new meadow and willow communities (Townsend 1975). Thus, a sufficiently high water level of Lake Athabasca that would usually inundate the delta was considered pivotal to maintaining the ecological integrity of the PAD.

“It now appeared that the recently constructed Bennett Dam on the Peace River in British Columbia was directly responsible for the reduction in Lake Athabasca water levels” (PADPG 1972, p. 4) — this statement from the Introduction of the PADPG Summary Report published in 1972 presents a clear cause for the ~1 m decline in Lake Athabasca water level. However, one study conducted as part of the PADPG investigations attempted to address this observation from a somewhat more scientific standpoint. Based on variations in tree-ring sequences collected from the PAD, Stockton and Fritts (1973) reconstructed water levels of Lake Athabasca back to the early 1800s to examine long-term water-level trends not evident in the relatively short and sporadic water-level gauge records, few extending back to the 1930s. The reconstruction was used to address the research question: Are the low water levels during the period of reservoir infilling (1968–1971) unusual or have similar water levels occurred under conditions of natural hydrological variability?

The Lake Athabasca water-level reconstruction, re-plotted in Fig. 2a, displays both long-term (multidecadal) and short-term (inter-annual) patterns of variability. Noteworthy features include (i) water levels were frequently as low as during 1968–1971, (ii) the ~1 m decline during the reservoir filling years is matched or exceeded several times in the tree-ring record, and (iii) a small decline in lake levels occurred immediately prior to reservoir filling (Stockton and Fritts 1973). Evidence thus suggested that the ~1 m decline in Lake Athabasca water levels during the filling period was not unprecedented. Collectively, these observations led Stockton and Fritts to conclude the downward trend in Lake Athabasca water level after 1967 was due to both climatic variation and impoundment of water behind the WAC Bennett Dam on the Peace River. (Timoney (2002) subsequently showed that other lakes and rivers in the region, including those unaffected by regulation, were also experiencing low levels and floods during this time.) Yet, this key finding was all but ignored in the final assessment of PADPG, which concluded that the WAC Bennett Dam had permanently altered the flow regime of the Peace River and caused low water levels on Lake Athabasca and lakes in the delta, and was expected to cause continued detrimental changes to the ecology of the delta. This perception provided the impetus to construct several flow control structures in the delta designed to hold water back in Lake Athabasca, one of which was subsequently removed because it had negative effects on water quality and formed a barrier to fish spawning migration (PADTS 1996). Other structures remain, but they have not replicated pre-regulation flow conditions (PADTS 1996).

Twenty years after the completion of the PADPG studies, renewed concerns over deteriorating ecological conditions in the PAD emerged as a result of extensive drying in the more elevated regions of the delta during the mid-1970s through the early 1990s. This reaffirmed the widespread paradigm that the delta was “dying” of “unnatural” causes and led to the launching of the PADTS from 1993–1996, and related research conducted as part of the Northern River Basins Study and subsequent Northern River Ecosystems Initiative. Several important scientific advances were made during these investigations. These mainly centered on generating new knowledge that refined understanding of how the PAD functions from a hydrological perspective and the recognition that both river regulation and climate change may be responsible for recently observed changes to the delta. These studies have been reviewed extensively elsewhere (Prowse and Conly 2000, 2002; Prowse et al. 2002, 2006). A particularly important finding can be traced to the observation that the largest open-water flow event on the Peace River (at Peace Point — see Fig. 1), which occurred in 1990, failed to recharge the high-elevation basins. While this observation was surprising at the time, it allowed hydrologists to determine that open-water floods have not been responsible for overbank flooding of the elevated perched basins, contrary to what previously was thought when the PADPG studies were undertaken (Prowse and Lalonde 1996). Instead, it became evident that

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periodic flooding produced by ice-jam backwater, which led to higher peak water levels than could be attained under open-water conditions, was the primary mechanism that led to replenishment of perched basins. Subsequently, several studies were conducted to explore the factors that control ice-jam flooding, to simulate “naturalization” of Peace River flows, and to characterize climatic conditions that could also contribute to the apparent decline in flood frequency and magnitude and their consequences for perched basin water balance (e.g., Prowse and Conly 1998; Peters and Prowse 2001; Peters et al. 2006a, 2006b; Romolo et al. 2006a, 2006b).

Given the importance of ice-jam flood events and concern that they had declined in frequency since river regulation, Timoney et al. (1997) undertook a study to reconstruct a flood history of the PAD to place current conditions into a longer-term context. A preliminary history of high-water events for the PAD spanning 194 years from 1803–1996 was developed using available information from a variety of local traditional knowledge and written records (Peterson 1995). Timoney et al. (1997) analyzed the record of flood events and used data beginning in 1826, and thus avoided the early part of the record deemed fragmentary and less reliable. They limited the analysis to include only events described as significant spring floods and which could be assigned to the Peace River. They coded the time-series as $0 = \text{no flood}$ and $1 = \text{flood}$ and then calculated running means using 5-, 10-, 20-, and 40-year periods (Fig. 2b). Results, as updated by Timoney (2002), indicated that 28 major ice-jam floods occurred on the Peace River between 1826 and 2000, yielding an average flood recurrence interval of approximately 6 years. The record also indicated the occurrence of a multidecadal dry–wet–dry cycle of lower-than-average flood frequency during the late 1800s and late 1900s and intervening higher-than-average flood frequency during the early to mid-1900s. A key concern in the post-regulation interval was the 22-year-long absence of ice-jam flooding of the delta between 1974 and 1996. Yet, the historical flood record contained evidence suggesting that >20-year intervals without flooding had similarly occurred during the late 1800s. In addition, the record suggested a decline in flood frequency had begun in the early 1900s, several decades before the Peace
River became regulated for hydroelectric production. However, the significance and magnitude of many of the flood events recorded by historical sources have been questioned because of the high spatial variability of flooding in such a complex water network and possible observer bias (Prowse and Conly 2002), and therefore, the study’s findings have rarely been mentioned in subsequent reviews.

**Paleolimnological studies in the Peace–Athabasca Delta**

After the PADTS were completed, changing climatic conditions emerged as another potential driver for the apparent reduction in flood frequency, in addition to river regulation. Research had identified that the driving forces of the breakup of the Peace River are the spring flow contribution from the tributaries downstream of the point of regulation. But, Prowse and Conly (1998) have suggested that regulation had reduced the relative impact of these forces by creating increased winter flows on the Peace River prior to breakup. In other words, more tributary flow was now required to generate dynamic breakup events because ice cover established at higher elevations could withstand greater flows before failing. Furthermore, climatic variation had led to a decline in Peace River tributary snowpacks since the mid-1970s (and thus less spring melt and discharge; Prowse and Conly 1998). Therefore, Prowse and Conly (1998) concluded that the apparent decline in flood frequency was likely a combination of river regulation and climatic effects. Remaining unknown, however, was the relative influence of river regulation and climate on the PAD ecosystem, and specifically how do the hydrology and ecology of hundreds of lakes in the PAD, and they were selected on the basis of contemporary water-isotope data obtained from ~60 lakes (Wolfe et al. 2007b) and field observations (e.g., evidence of recent water-level changes). The complex sedimentary processes in the basins required an analytical strategy that integrated radiometric measurements (210Pb, 137Cs, 14C), which were used to establish sediment core chronologies, and a broad range of physical (loss-on-ignition, structure, texture, mineralogy, magnetic susceptibility), geochemical (organic carbon and nitrogen elemental and stable isotope composition, cellulose oxygen isotope composition), and biological (diatoms, plant macrofossils, pigments) information, which was used to reconstruct past changes in hydroecological conditions. Details of these specific methods are contained in the individual publications highlighted below. Here we summarize key findings from these investigations.

**Establishing confidence in the paleolimnological approach**

As we embarked on our paleolimnological study, there were some apprehensions. Would these very shallow lakes (most are <2 m deep) contain well-preserved stratigraphic records, undisturbed by mixing due to physical or biological processes? Would the complement of paleolimnological tools that we intended to employ be sufficiently sensitive and reliable to track hydroecological changes that had occurred in the past? Could the hydroecological complexity of the PAD and its evolution be deconstructed from multiple stratigraphic records? Aware that the research would be carefully and critically scrutinized, we sought means to verify the results we were generating. An excellent opportunity emerged out of a research workshop organized by BC Hydro in June 2002, where we became aware of a series of historical maps and aerial photographs assembled by a consulting company that depicted marked hydrological changes in the interior of the PAD since 1884 (Mollard et al. 2002). Fortuitously, we subsequently discovered earlier maps, one from 1827 at the Fort Chipewyan Bicentennial Museum following a presentation we delivered to the local community in March 2005, and another from 1814 at the Canadian Museum of Civilization in Ottawa in December 2007. As we relay below, the hydrological history evident in the collection of maps and images aligned remarkably well with a stratigraphic record that we had generated from one of the lakes we cored, and, in fact, was instrumental in the interpretation of this record.

“PAD 9” (informal name; 58°46′N, 111°19.48′W, 209.82 m a.s.l.) is a small (~12 ha), shallow (maximum depth ~1 m), closed-drainage, open-water wetland, located ~10 km northwest of Lake Athabasca in a lowland region of the delta (Fig. 1). A large (~70 km²) flat flood-prone sedge meadow known locally as Fort Chipewyan Bay is situated between PAD 9 and Lake Athabasca. PAD 9 was selected for paleolimnological reconstruction because of its central location within the delta and the presence of drowned willow fringes adjacent to the modern shoreline, which indicated this basin had experienced recent water-level fluctuations — evidence that we anticipated would be contained in the sediment record.

Multiple analyses on a series of radiometrically dated, 30-cm-long gravity cores indicated that PAD 9 had witnessed marked hydroecological changes over the past ~400 years that, on the basis of the stratigraphic profiles and accompanying
Reconstructing flood frequency and magnitude from laminated sediments in oxbow lakes

The absence of a major ice-jam flood event between 1974 and 1996 was a key contributor to widespread perception that flow regulation by the WAC Bennett Dam reduced flood frequency and magnitude. To address this perception, a paleoenvironmental perspective on flood events was needed to evaluate the significance of this seemingly long period without widespread river-derived recharge of the PAD. Indeed, lack of knowledge of natural variability in the frequency of ice-jam floods was likely a major impediment in recognizing climate as the main driver of hydroecological conditions in this freshwater landscape, despite the efforts of Peterson (1995) and Timoney et al. (1997) mentioned above. Our approach centered on high-resolution analysis of laminated sediments from oxbow lakes (PAD 15, 54) located along channels that serve as distributaries of the Peace River during ice-jam flood events (Fig. 1), an approach also recommended by the PADTS (1996). These basins preserve exceptional decipherable records of flood events through time.

In the PAD and other remote locations, river discharge records are fragmentary, short in duration, and capture an insufficient range of climatic conditions, but they are often the only source of hydrological information available for developing water resource policy. Along the Peace River, the closest river gauging station to the PAD is located at Rocky Point, near the junction with the Chenal des Quatre Fourches (Fig. 1). The daily water-level record for Rocky Point was established in 1972 (after completion of the WAC Bennett Dam) and there are several notable gaps (Fig. 5a). These include during the spring of 1972, 1974, 1996, and 1997 when major ice-jam events damaged the gauging station (D. Smith, University of Calgary, personal communication 2002). Therefore, knowledge of peak river levels — a key hydrologic measurement to address the prevailing controversies — was missing or unreliable during these years. As noted by Peters et al. (2006b), “Unfortunately, a relatively short period of available hydrometric observations within the delta (>1970s) and the intermittent loss of records during extreme events (i.e. as a result of loss of gauging equipment during dynamic ice scour events) precludes statistically valid analyses of trends in the time series” (p. 4074).

In contrast to the hydrometric stations, the laminated sediments of oxbow lake “PAD 15” (informal name; local name: Pete’s Creek; 58°56′N, 111°29.32′W, 208.94 m a.s.l., ~16 ha, 4 m maximum depth; Fig. 1) provided a well-preserved and continuous paleohydrological record, which we have interpreted on the basis of several types of paleolimnological data to reflect variations in ice-jam flood frequency and magnitude (Wolfe et al. 2006, 2008a; Jarvis 2008). For example, C/N ratios (calculated by weight) from two gravity cores obtained in two different locations in PAD 15 and collected in different years (2001 and 2005) captured remarkably consistent variations in which increases in C/N ratios (interpreted to reflect greater supply of C-rich, N-poor, allochthonous, river-transported materials) correspond with known flood events over the past 35 years (Fig. 5b). These included (i) the major ice-jam flood events of 1972, 1974 (considered representative of the largest historical flood; Peters et al. 2006b), 1996, and 1997, (ii) less-extensive ice-jam flood events of 1979 and 1994 (Peters 2003), and (iii) the historical open-water maximum

historical maps and aerial photographs, could readily be reconciled into three distinct phases (Sinnatamby et al. 2010; Fig. 3). From ~1600 to ~1875 CE (Phase 1), diatom taxa indicative of open-drainage conditions (Staurosirella pinnata and Staurosira construens var. venter), moderate quartz content, high concentrations of Chara oospores, and cellulose-inferred lake water δ18O (δ18Ow) values similar to modern-day δ18O measurements of Lake Athabasca were collectively consistent with maps that depicted a lake-level highstand of Lake Athabasca. At this time, PAD 9 was likely strongly influenced by periodic inundation by low-energy flooding from Lake Athabasca outflow. Subsequently, between ~1875 and ~1925 (Phase 2), quartz content doubled, δ18Ow values declined to those similar to modern-day Athabasca River water, and the abundance of ostracod remains and Chara oospores declined markedly. Inferred conditions from these data corresponded to maps indicating a reduction in Lake Athabasca water levels and establishment of high-energy flow-through conditions that influenced PAD 9. Finally, post-1925 (Phase 3), increases in abundance of closed-drainage diatom taxa (mainly Cocconeis placenta), ostracode remains, emergent aquatic and terrestrial plants (Typha latifolia and Salix spp.), percent organic carbon, and δ18Ow values to those similar to modern-day PAD 9 water were compatible with images that showed further reduction in Lake Athabasca water levels. This reduction led to establishment of a closed-drainage hydrological setting characterized by productive, low-energy-conditions, features that define the current state of the PAD 9 basin.

Paleohydroecological coherence of the PAD 9 stratigraphic record, aided by the visual context provided by the archival maps and aerial photographs, was an especially critical finding for our study as it firmly established confidence in the approaches and methods we were using. Many important technical concerns were resolved. Namely, (i) stratigraphic records were not disturbed by mixing, (ii) sediment cores could be reliably dated using standard radiometric techniques, and (iii) multiple paleolimnological analyses could provide informative paleohydroecological reconstructions. Perhaps even more important was the discovery that dramatic hydrological changes had recently occurred in the central interior of the delta over a surprisingly short period of time, later substantiated by paleolimnological and geophysical investigations on Bustard Island in western Lake Athabasca (Johnston et al. 2010). Not even 100-years-ago, this portion of the delta was often submerged under a shallow embayment of Lake Athabasca because of greater summer river discharge during the Little Ice Age (LIA), and undoubtedly appeared very different than it does today (Fig. 4). We cite this factor (i.e., the marked declines in water levels in areas of the PAD adjacent to Fort Chipewyan since the 1920s) as contributing to the perception that the delta has been drying and dying by unnatural causes (Sinnatamby et al. 2010; Johnston et al. 2010). Indeed, the profound changes depicted by integration of these independent lines of evidence dwarfed any hydroecological changes that have occurred since the WAC Bennett Dam was constructed. Clearly, drying began in the early 20th century well before regulation of the Peace River.
Fig. 3. Paleolimnological record from PAD 9, and accompanying interpretations of historical maps (modified from Sinnatamby et al. 2010). For the full sequence of historical maps and aerial photos, see Sinnatamby et al. (2010).

Fig. 4. Modified digital elevation model of Peters et al. (2006b) with location of PAD 9 identified. Bold contour line identifies the 211 m a.s.l. water plane during the “Little Ice Age” (modified from Johnston et al. 2010).
The flow event of 1990 (Prowse and Lalonde 1996). Furthermore, the non-flood interval of the 1980s was readily apparent in these records, characterized by low and less variable C/N ratios. Within this brief 35-year interval, the 1974 flood stands out as a major hydrological event. As shown in Wolfe et al. (2006), several other physical and geochemical parameters also displayed variations corresponding to the known recent flood history.

Magnetic susceptibility proved to be a particularly sensitive recorder of flood frequency and magnitude, evidently reflecting the influx of Fe- and (or) Mg-rich minerals delivered by the Peace River. Along with mineral sediment, bitumen eroded from upstream deposits likely contributed to the dark appearance of these flood-derived laminations (Wolfe et al. 2006). Based on these analyses performed on a 4.06-m sediment sequence from PAD 15 that spans ~300 years, flood frequency and magnitude have varied substantially (Fig. 5).

Key features of the record included (i) intervals of high flood frequency from ~1785–1815 CE and from ~1875–1900 CE, (ii) markedly low flood frequency during the 1700s, (iii) a decline in flood frequency beginning about 1900, and (iv) several multidecadal intervals without major floods during the past 300 years that are similar to or longer than the 1975–1995 interval. In the context of the past three centuries, the 1974 flood remains a prominent event and provides a useful benchmark for identifying that 14 flood events equal to or greater than the 1974 flood over the past 180 years (Wolfe et al. 2006). Notably, sediment-inferred patterns of flood frequency closely corresponded with the historical-based flood record of Timoney et al. (1997; Fig. 2b), which lent considerable credence to both approaches. Furthermore, these data suggested that flood frequency had been in decline for several decades preceding Peace River regulation and that multidecadal periods without flooding were not unusual occurrences. These findings highlighted the variable nature of ice-jam flood frequency in this landscape, independent of human influence or intervention (Wolfe et al. 2006).

A much greater appreciation for the over-arching role of climate variability and change on Peace River ice-jam flood frequency and magnitude was acquired from magnetic susceptibility measurements on a ~600-year record we subsequently retrieved from PAD 15 with an ice-based monopod vibra-core system in March 2005 (Fig. 5; Wolfe et al. 2008a). Given this longer temporal perspective, the 1974 flood event is barely perceptible because of the very high flood frequency and magnitude that typified the relatively warm and moist Medieval Period (pre-1600 CE). We interpreted the frequent and massive flooding during the Medieval Period to have been driven by rapid spring-melt of abundant snow accumulation in the mid-elevation portions of the watershed. Flood frequency and magnitude rapidly dissipated with cooling during the LIA, which delayed and prolonged the spring freshet, and thus was less conducive for ice jams to develop. Decline in snowmelt runoff during the 20th
Determining lake water balance history

The absence of a major ice-jam flood in the two decades that followed the 1974 flood event resulted in reduced water levels in many perched basins, well-illustrated in a composite change detection enhancement of August 1976–1981–1985 Landsat images of the PAD (Fig. 6). Red, orange, and yellow hues identify areas that underwent significant drying between 1976 and 1985. These included large portions of the low-lying interior and the more elevated northern part of the delta. Based on these images, the rate of drying was used to project that perched-basin open water will disappear in ~15–20 years if significant flooding does not occur, which would have associated negative ecological consequences (EcoStat Geobotanical Surveys 1988). Concern over drying of the perched basins led us to focus much of our paleolimnological efforts on these types of lakes, driven by the need to answer the following: (i) Is there evidence that flow regulation of the Peace River has caused discernible, directional changes in hydroecological conditions in perched basins, and, more broadly, (ii) How is hydroecological variability of the perched basins related to climate variability and flood history? Our approach was to utilize multiple physical, geochemical, and biological measurements on lake sediment cores to reconstruct past hydroecological conditions, as demonstrated in Fig. 3 and in several publications (Edwards et al. 2004; Wolfe et al. 2005, 2007a, 2008a, 2008b; Leng et al. 2006; Sinnatamby et al. 2010; Wiklund et al. 2010; McGowan et al. 2011).

An especially informative indicator in a number of cases was the oxygen isotope composition of aquatic cellulose, which we used to directly trace lake water-balance history (Wolfe et al. 2001, 2007a). For our studies in the PAD, we relied upon water-isotope monitoring to identify the relative roles of contemporary hydrological processes that control the lake water balances in this landscape (Wolfe et al. 2007b; Yi et al. 2008; Wiklund et al. 2012a). These data also provided important constraints on the interpretation of cellulose-inferred lake water oxygen isotope records preserved in lake-bottom sediments (Wolfe et al. 2005, 2008a, 2008b; Sinnatamby et al. 2010). Knowledge gained has placed recent observations of low lake levels into a longer temporal context — insight required to determine the primary factors that drive lake water-balance variability. Below we illustrate the usefulness of this approach with results from several years of water-isotope monitoring of two small, shallow (~1 m) perched basins in the northern Peace sector, as well as key water sources (Lake Athabasca and the Peace River), and their corresponding cellulose-inferred lake water oxygen isotope histories of the past 1000 years.

We monitored the water-isotope composition of “PAD 5” (Spruce Island Lake, informal name; 58°50′N, 111°28.84′W, 209.89 m a.s.l., ~22.5 ha), “PAD 12” (informal name; 58°57′N, 111°19.74′W, 209.79 m a.s.l., ~5 ha), Lake Athabasca, and the Peace River over a 6-year period (October 2000 to September 2006), which revealed distinct ranges in isotopic signatures for these different waters (Figs. 1, 7a, 7b). As shown on a conventional δ18O-δ2H diagram (Fig. 7a), waters plot along different segments of the predicted local evaporation line (Wolfe et al. 2007b), reflecting varying degrees of evaporative isotopic enrichment. Generally, and as expected, the small, perched lakes PAD 5 and PAD 12 were more isotopically enriched (i.e., higher δ-values) than Lake Athabasca and the Peace River because evaporation was a more important component of the perched basin lake water balance. Isotopic values for PAD 5 spanned the greatest range (δ18O = −13.4‰ to −3.8‰; δ2H = −132‰ to −82‰), reflecting strong sensitivity to hydrological processes, including the input of isotopically-depleted snowmelt in the spring from its forested catchment and subsequent isotopic enrichment over the course of the ice-free season because of evaporation (Fig. 7b). Likewise, PAD 12 showed similar isotopic behaviour (δ18O = −13.7‰ to −5.6‰; δ2H = −128‰ to −93‰), although snowmelt tended to cause greater isotopic depletion in lake water values in the spring and subsequent isotopic enrichment because of summer evaporation tended to be less. Conversely, a lower and narrower range of values defined Lake Athabasca water (δ18O = −18.1‰ to −14.8‰; δ2H = −142‰ to −126‰). The lower values were due to lesser influence of evaporation on the lake water balance, while the large volume of the lake buffered seasonal hydrological effects. The Peace River contained the most isotopically-depleted values (δ18O = −21.1‰ to −17.7‰; δ2H = −165‰ to −141‰) of these four waters because of the very small to negligible influence of evaporation. Overall, the ~20‰ range in contemporary δ18O values among these four waters revealed the sensitivity of water-isotope tracers to specific hydrological settings in this landscape, which we have utilized to interpret changes in cellulose-inferred lake water oxygen isotope records from sediment cores and to identify their causes (Fig. 7c).

Cellulose-inferred lake water δ18O records (δ18Ow) for PAD 5 and PAD 12 spanning the past 1000 years showed remarkably similar patterns (Fig. 7c). Both δ18Ow records contained much lower values from 1000 to 1600 CE (PAD 5: −19‰ to −16‰; PAD 12: −22‰ to −19‰) compared with the modern lake settings. At 1600 CE, δ18Ow increased rapidly at both lakes, although the PAD 5 δ18Ow record attained much higher values (~−8‰ to −5‰) than the PAD 12 δ18Ow record (~−17‰ to ~−15‰). While δ18Ow values remained high at PAD 5, δ18Ow values for PAD 12 declined to ~−20‰ to ~−17‰ between ~1650 until ~1825 CE before generally increasing to values of ~−16‰ to ~−14‰ in the latter half of the 20th century. δ18Ow values at PAD 5 declined to ~−11‰ at the end of the LIA and then increased to ~−9‰ over the course of the 20th century.

We have used the δ18Ow records from PAD 5 and PAD 12 to highlight hydrological responses to past changes in river hydrology and climate during the Medieval Period (1000–1600 CE), LIA (1600–1900 CE), and post-LIA interval, incorporating information from paleolimnological records obtained from additional locations in the PAD (Wolfe et al. 2008a). Here we provide additional details, explicitly focusing on the knowledge provided by contemporary isotopic monitoring of the sites (Figs. 7a, 7b) that constrained the paleohydrological reconstructions. During the Medieval Period, very low δ18Ow values at both PAD 5 and PAD 12 were in agreement with contemporary water δ18O values we have
measured for the Peace River. This was also consistent with
the PAD 15 magnetic susceptibility record, which revealed
that frequent and high-magnitude ice-jam flooding character-
ized this interval (Fig. 5d), evidently strongly influencing the
water balances of PAD 5 and PAD 12. The frequency and
magnitude of river flooding decreased markedly during the
LIA (Fig. 5d) and, correspondingly, the $\delta^{18}O_{\text{lw}}$ values in-
creased because evaporative enrichment occurred due to drier
climatic conditions of the LIA in this region. The $\delta^{18}O_{\text{lw}}$ re-
cord at PAD 12 did not undergo the same degree of evapora-
tive enrichment and, in fact, shifted to lower values because
rising water from Lake Athabasca flooded into the basin at
this time en route to the Slave River (Johnston et al. 2010).

PAD 12 is currently situated at an elevation of about 2.8 m
above the Rivière des Rochers near the confluence with the
Peace River, and with Lake Athabasca ~2.3 m higher than
present during the LIA (Johnston et al. 2010) these waters
could readily have entered the PAD 12 basin during flood
events. $\delta^{18}O_{\text{lw}}$ values during this interval are ~2‰ lower
than what we have captured in Lake Athabasca during the
monitoring period, likely because of increased meltwater dis-
charge at this time. The post-LIA increase in $\delta^{18}O_{\text{lw}}$ values at
PAD 5 aligns with average lake water $\delta^{18}O$ measured at this
date during the monitoring period, whereas uppermost $\delta^{18}O_{\text{lw}}$
values at PAD 12 suggest cellulose at this site is dominantly
produced during the early thaw season when the lake is most
affected by isotopically-depleted snowmelt runoff. Notably,
and consistent with the evidence we found at PAD 9, the
post-LIA increase in evaporative isotopic enrichment at PAD
5 and PAD 12 began decades before regulation of the Peace
River.

Overall, the similarity in the lake sediment cellulose $\delta^{18}O$
records, and direct translation to meaningful lake water $\delta^{18}O$
values consistent with contemporary isotopic measurements,
are key features that highlight the robust nature of this ap-
proach for reconstructing past hydrological conditions in this
landscape. In these examples, findings documented marked
variability in lake water balances over time extending well
beyond recent observations of the past 40 years. Notably,
these and other hydroecological reconstructions (e.g., Figs. 3,
5) provided no compelling evidence to suggest that flow reg-
ulation of the Peace River has had any discernible, direc-
tional hydrological or ecological effects on the perched
basins of the Peace sector of the delta. Rather, changes in
the overall state of the Peace sector appear to have been
driven predominantly by ongoing warming, drying, and natu-
really declining river discharge over the past century — a
finding that also corresponds with declining flood frequency
as documented by Timoney et al. (1997; see Fig. 2b).
Identifying geomorphic modification to Athabasca River flow as a driver of recent hydroecological change

Following a series of paleolimnological studies in the northern, Peace sector of the PAD, which are highlighted above, we turned our attention to the southern, Athabasca sector (an area containing the Athabasca Delta, generally south of lakes Mamawi and the western end of Athabasca). Remarkably, despite more than 30 years of study, very little attention had been given to the role of the unregulated Athabasca River on the delta (notable exceptions include: Peters and Prowse 2006; Peters et al. 2006b), yet this river provides the largest direct and continuous flow of water to the PAD and Lake Athabasca. Therefore, we suspected that there may be considerable potential for large-scale hydroecological changes to occur in the Athabasca Delta in response to changes in the Athabasca River.

Fortuitously, recent engineered and natural geomorphic changes to the Athabasca River and its distributaries provided an ideal experiment for us to evaluate the hydroecological consequences of recent flow regime changes on 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”; see Figs. 1, 8a). The construction of the channel alleviated concerns, albeit temporarily, that substantial flow would bypass Chipewyan Indian Reserve 201 (Fig. 1) to the northeast if a natural avulsion had been allowed to develop. Ten years later, however, natural bifurcation of the Embarras River farther downstream diverted flow northwest through Cree and Mamawi creeks (the “Embarras Breakthrough”; Figs. 1, 8b), which discharge into Mamawi Lake in the central portion of the PAD. As we highlight below, paleolimnological records spanning the 20th century from well-positioned study lakes, and spatial distribution of floodwaters captured by water-isotope analysis, demonstrated that recent changes in the flow regime of the Athabasca River have indeed had a profound influence on the hydroecology of the Athabasca Delta (Wolfe et al. 2008b).
water depth) perched basin located near the southern margin and more elevated region of the Athabasca Delta, and it is 5 km southeast of the Athabasca River Cut-Off (Fig. 1). As revealed by multiple analyses on sediment cores from PAD 23, this engineered change in Athabasca flow substantially affected the hydroecology of this basin (Fig. 8a). Based on several indicators, the lake was frequently affected by river floodwaters prior to the Cut-Off. These included low $\delta^{18}O_{lw}$ values that were similar in composition to present-day Athabasca River water $\delta^{18}O$ and high relative abundance of diatoms indicative of open-drainage conditions. Organic carbon content and $\beta$-carotene (total algal abundance) concentration were also low until ~1975 and ~1980, respectively, because of reduced light availability and dilution by increased detrital input and minerogenic turbidity associated with river flooding. At ~1940, there was a sharp increase in concentration of leaves of Drepanocladus (submerged aquatic moss) 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 than at present. After the Cut-Off (1972), multiple paleolimnological analyses captured directional hydroecological change associated with reduced frequency of river floodwaters entering the basin (Fig. 8a). Paleolimnological evidence for reduced river flooding included an increase in $\delta^{18}O_{lw}$ values because of greater importance of evaporation to the lake water balance,
increased organic carbon content and \( \beta \)-carotene concentration resulting from increased aquatic production, higher abundance of closed-drainage indicator diatoms, and increased abundance of \textit{Sphagnum} (moss) leaves reflecting the development of floating \textit{Sphagnum} beds that currently exist along much of the lake’s margin.

“PAD 31” (informal name; local name: Johnny Cabin Pond; 58°29’N, 111°31.17’W; ~209 m a.s.l.) 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. In contrast to the recent drying at PAD 23, this natural geomorphic event increased flood frequency at PAD 31 (Fig. 8b). Prior to ~1980, most \( \delta^{18}O_{\text{os}} \) values were higher relative to present-day Athabasca River water \( \delta^{18}O \) values, indicating the important role of evaporation on water balance with moderate influence from river flooding. Organic carbon content, \( \beta \)-carotene concentration, terrestrial plant macrofossil concentration (mainly comprising shoreline herbs such as \textit{Chenopodium}, \textit{Rumex}, \textit{Rorippa}, and \textit{Potentilla palustris}; Hall et al. 2004), and \textit{Scirpus} seed concentration were low during 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, began to increase until ~1970 suggesting reduced river flooding. The most pronounced changes occurred after the Embarras Breakthrough (after ~1982), marked by a rapid decline and, after ~1995, more variable \( \delta^{18}O_{\text{os}} \) values consistent with increased magnitude and frequency of river flooding. Terrestrial plant macrofossils also declined while organic content and \( \beta \)-carotene concentration remained high, likely reflecting lake deepening and stimulation of algal growth during the initial phase of increased river input. \textit{Scirpus} seeds continued to increase in concentration, also consistent with higher or seasonally variable water levels. The 1990s were the decade of strongest and most persistent river flooding during the past century at PAD 31, based on highly variable \( \delta^{18}O_{\text{os}} \) values consistent with increased magnitude and frequency of river flooding. Terrestrial plant macrofossils also declined while organic content and \( \beta \)-carotene concentration remained high, likely reflecting lake deepening and stimulation of algal growth during the initial phase of increased river input. \textit{Scirpus} seeds continued to increase in concentration, also consistent with higher or seasonally variable water levels. The 1990s were the decade of strongest and most persistent river flooding during the past century at PAD 31, based on highly variable \( \delta^{18}O_{\text{os}} \) values consistent with increased magnitude and frequency of river flooding. Terrestrial plant macrofossils also declined while organic content and \( \beta \)-carotene concentration remained high, likely reflecting lake deepening and stimulation of algal growth during the initial phase of increased river input. \textit{Scirpus} seeds continued to increase in concentration, also consistent with higher or seasonally variable water levels. The 1990s were the decade of strongest and most persistent river flooding during the past century at PAD 31, based on highly variable \( \delta^{18}O_{\text{os}} \) values consistent with increased magnitude and frequency of river flooding.

A key element of this research was recognition that the divergent and directional hydroecological responses to geomorphic-driven changes in the Athabasca flow regime during the past three to four decades at these two locations appeared to be representative of conditions that have developed across the Athabasca Delta (Wolfe et al. 2008b). This was deduced from the isotope mapping of an ice-jam flood event in 2003 (Fig. 9). The southwest–northeast blue swath through the Athabasca Delta in Fig. 9 includes basins that received large volumes of primarily river water as a result of flooding, whereas the red zone in the southeast includes basins that were not flooded. PAD 31 was flooded during this event while PAD 23 and “PAD 39” (whose paleolimnological record is also reported in Wolfe et al. 2008b) were not. As noted in Wolfe et al. (2008b), these results aligned with recent trends in the paleolimnological records from these basins. Thus, the 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. These findings led to the conclusion that the hydroecology of the Athabasca sector of the PAD is far more sensitive to changes in Athabasca River flow, whether natural or anthropogenic, than the northeastern Peace sector is to changes in Peace River flow — a conclusion that should not be surprising given that the Athabasca River flows directly into the delta, whereas the Peace River waters only enter the delta occasionally. Consequently, Wolfe et al. (2008b) identified the importance of policies and governance structures to ensure environmental flows via the Athabasca River to the Athabasca Delta.

Climate change and declining freshwater variability in western North America — a multimillennial perspective

We have reiterated the message contained in the concluding sentence of the preceding section in subsequent publications. Initially, a series of 1000-year paleolimnological records including those of PAD 9 (Fig. 3; extended to the past millennium), PAD 15 (Fig. 5), and PAD 5 and PAD 12 (Fig. 7) illustrated that the seasonality and volume of river discharge draining the eastern slopes of the Rocky Mountains have fluctuated markedly in response to climate changes over the past millennium (Wolfe et al. 2008a; Fig. 10). Assembled evidence, including a decadally resolved tree-ring-based reconstruction of winter temperatures and growth-season relative humidity (Edwards et al. 2008), indicated that a unique array of hydrological conditions had characterized the PAD during the 20th century. Results showed that during this century, the reduced influence of the Peace and Athabasca rivers had led to the lowest flood frequency and water levels of the past millennium in most areas of the PAD. We attributed this to a consequence of shrinking headwater glaciers and decreasing snowmelt runoff since the end of the LIA (ca. 1900). Furthermore, we speculated that the transition to the “future scenario” (Fig. 10), defined by yet further reductions in river discharge during the spring freshet and summer, was well underway (Wolfe et al. 2008a).

But our most compelling evidence for rapidly declining freshwater availability, perhaps somewhat ironically, originated from paleolimnological data obtained from outside of the PAD. In spring 2003, we identified two small lagoonal ponds on Bustard Island in western Lake Athabasca from an aerial photograph of the region hanging on the wall in the former Fort Chipewyan Lodge. At the time, we were grappling with the intricacies of the many stratigraphic records that we had obtained from the PAD, but were beginning to appreciate the important role that multidecadal to centennial variations in Lake Athabasca water levels had played on the delta, as described above (see section Establishing confidence in the paleolimnological approach). We raised the possibility that perhaps these lagoonal sediments, located distant from the complexity of the PAD, might archive a direct record of past Lake Athabasca water-level history to complement the story that was emerging from the PAD 9 stratigraphy and the historical maps. Sediment cores were collected in July 2004 from “North Pond” (informal name: 58°48’N, 110°45.56’W), Bustard Island, to test this hypothesis.

Among various lake sediment core analyses, C/N weight ratios provided a straightforward link to identify episodes of expansion and contraction of the relict lagoon in response to rise and fall in Lake Athabasca water levels driven by changing Athabasca River discharge (Wolfe et al. 2008a, 2011; Johnston et al. 2010; Fig. 11). The 5200-year lake-level
reconstruction that materialized from calibration of the C/N stratigraphic profile revealed that early 20th century society in western Canada developed during a rare interval of relatively abundant freshwater supply, fueled in part by melting glaciers and icefields that accumulated during the LIA (~1600–1900 CE). This subsidy to river flow has been diminishing rapidly over the past century. Equally disconcerting is that freshwater has only been in similar plentiful supply during one other multicentennial interval (~2300–1500 BP) of the past ~5200 years. But the most important result was evidence for a multimillennial ~2–4 m lowstand during the mid-Holocene, a time absent of known glacier advances in the Rockies (Clague et al. 2009) that may very well define the near future. The reconstruction also indicated that the transition from water abundance to scarcity can occur within a human generation, allowing little time for society to adapt. These findings, which we regard as the most important in our 12 years of research in this complex landscape, have critical implications for management of the freshwater resources and ecological integrity of one of the most diverse, internationally designated areas in the world. If water allocation guidelines are derived solely on the basis of the relatively brief and often sporadic instrumental hydrometric record, without accounting for anticipated reduction in high-elevation precipitation and runoff (Lapp et al. 2005; Sauchyn and Kulshreshtha 2008; Pederson et al. 2011), then the magnitude and rate of decline in freshwater supply because of climate warming may be grossly underestimated. Based on recent trend analysis, Rasouli et al. (2012) predicted Lake Athabasca water levels reminiscent of the mid-Holocene Lowstand could occur by 2100. Other jurisdictions in western North America that rely on streamflow generated from alpine ice and snow face similar challenges (Wolfe et al. 2011).

Recent history provides a poignant reminder. The short-lived ~1 m decline in Lake Athabasca water levels between 1968 and 1971 sparked >40 years of controversy and conflicts at a national scale over utilization of water resources that has persisted to the present. Inaccurate understanding of the cause (Peace River regulation by the WAC Bennett Dam) of the effect (reduced water levels and flood frequency in the nation-wide designated areas in the world. If water allocation guidelines are derived solely on the basis of the relatively brief and often sporadic instrumental hydrometric record, without accounting for anticipated reduction in high-elevation precipitation and runoff (Lapp et al. 2005; Sauchyn and Kulshreshtha 2008; Pederson et al. 2011), then the magnitude and rate of decline in freshwater supply because of climate warming may be grossly underestimated. Based on recent trend analysis, Rasouli et al. (2012) predicted Lake Athabasca water levels reminiscent of the mid-Holocene Lowstand could occur by 2100. Other jurisdictions in western North America that rely on streamflow generated from alpine ice and snow face similar challenges (Wolfe et al. 2011).

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The evolution of hydrographs for rivers draining the eastern slopes of the Rocky Mountains over the past millennium and anticipated future (Wolfe et al. 2008a, p. 4). Schematic profiles are based on assemblage of multidenitential paleoclimate and paleolimnological records reported in Wolfe et al. (2008a) and expected trends.

PAD) lie at the center of the conflicts and provided impetus for costly remediation to mitigate effects of river regulation. Given the prospects of an extended ~2–4 m lake-level drop relative to the 20th century, as occurred during the mid-Holocene Lowstand (Fig. 11), government and industry must now face the possibility of water scarcity in the decades to come. How will we respond this time?

Lessons learned

Over the course of our 12-year research program, there have been many lessons learned that are useful to relay to others (e.g., researchers, water-resource managers). Scientifically, we have made substantial effort to characterize contemporary hydrological and limnological conditions using water-isotope tracers in combination with standard water chemistry analyses (Wolfe et al. 2005, 2007a, b; Yi et al. 2008; Wiklund et al. 2012a), as well as their relations with paleolimnological indicators (Hall et al. 2004; McGowan et al. 2011). This involved numerous sampling campaigns, including extended field stays by our students. These were especially useful approaches that provided new insights into modern processes and intimate awareness of contemporary ecosystem functioning, knowledge that was also critical for informed and well-constrained interpretation of paleolimnological records (e.g., see Fig. 7; also Wolfe et al. 2005, 2008a, 2008b; Sinnatamby et al. 2010). Also, paleolimnological studies included several lakes situated in different hydrological settings and, as a result, their sediments varied from highly minerogenic to organic. Consequently, no single type of data sufficed at all sites; rather, use of multiple types of physical, geochemical, and biological data were required. But this complexity also provided novel research opportunities. For example, using an innovative experimental design that was based on our contemporary hydrolimnological knowledge of the PAD, we have developed a promising new paleolimnological tool to reconstruct flood events from diatoms, which is likely transferrable elsewhere for tracking other pulse-type disturbances (Wiklund et al. 2010). We consider these aspects to be key strengths in our approach to unravelling the natural history of this freshwater landscape, and also represent useful methods for establishing a much-needed hydroecological monitoring program for the PAD (see below). Also, we are now utilizing our paleolimnological knowledge in the PAD to establish baseline information for assessing contamination by the Alberta oil sands development (Wiklund et al. 2012b; Hall et al. 2013).

An important factor that allowed us to carry out this extensive research was access to substantial funding from several sources (i.e., industry and government) well beyond the level typically available to academic scientists. Initially, research was largely supported by BC Hydro, motivated by litigation, who provided a ~$2 million research contract (2000–2003). This was subsequently used to leverage other major grant proposals. While ample research funds were needed to perform the research as designed, they also provided flexibility to pursue new emerging ideas and to take risks. For example, investigations on Bustard Island were not described as part of any major research proposal, but instead were supported by existing funds that we had available at the time. Funding also provided exceptional field and laboratory training opportunities for students at all academic levels with interests in hydroecological research. Interactions among our collaborative team of faculty and their students, including delivery of numerous presentations at conferences, provided opportunity for innovative thinking and peer review that led to new insights.

Partnership with industry during the early phases of our research had many benefits beyond financial support. BC Hydro played an important role in the dissemination of findings to key stakeholders. For example, travel support was provided to present research findings to staff of Wood Buffalo National Park (Fort Chipewyan, September 2002) and to provincial government scientists and managers of Alberta Environment and British Columbia Ministry of Environment to inform transboundary water management negotiations (Edmonton, September 2005). BC Hydro published a comprehensive peer-reviewed report on our findings (Hall et al. 2004), much of which has since appeared in mainstream peer-reviewed literature, and provided funding for the Wilfrid Laurier University Cold Regions Research Centre Symposium on Managing Water in the Peace–Athabasca–Slave River Corridor (Waterloo, April 2005). This symposium brought together over 50 researchers and stakeholders from industry, government, and academia to review the current state of knowledge on the hydroclimatological and hydroecology of the Peace–Athabasca and Slave River deltas, and importantly facilitated open dialogue among participants.

Notably, the building of this partnership with industry required substantial time and effort. Numerous reports were prepared for BC Hydro and frequent travel to Vancouver was required to present preliminary research findings between October 2000 and December 2005. Such tasks were demanding in terms of time commitment but were clearly of considerable importance.

and mutual benefit. Indeed, these were the critical formative steps in the building of the successful partnership. A key feature of our frequent face-to-face meetings was opportunity to report on research progress to a panel of other leading experts in paleoenvironmental science, which was facilitated by BC Hydro. This advisory committee provided an early stage of peer review and feedback, which we could use to strengthen the quality of research conducted and the scientific product. For example, one advisory committee member suggested use of magnetic susceptibility as an approach to analyze the laminated sediments from PAD 54 and PAD 15, which we employed to generate highly informative flood records (Fig. 5). Industry-supported research has also presented some challenges, as the source of the funding has inevitably led to skepticism about our findings. We contend that the level of support from BC Hydro, in addition to NSERC and other agencies, fostered and accelerated independent collaborative, multidisciplinary, and innovative environmental research, which provided a robust set of results to answer critical and fundamental research questions.

**Implications and recommendations**

Below we identify implications that stem from the findings of our paleoenvironmental research in the PAD and propose features of a hydroecological monitoring program, which we regard as essential foundation to inform ongoing and future water resource management decisions in this world-renowned landscape.

**Implications**

1. The PAD is a dynamic system that is sensitive to variability in climate and river hydrology. Consequently, the delta should not be managed to maintain it as a static system.
2. The PAD consists of at least three distinct sectors (i.e., northern relict Peace Delta, central lowland interior, southern active Athabasca Delta) that respond differently to variability in climate and river hydrology. Consequently, the delta should not be managed uniformly as a single system.
3. The processes that drive changes in the PAD operate over a broad range of spatial and temporal scales. This feature has made it extremely difficult to identify correctly the causes of observed changes. Our results provide no discernible evidence to suggest that regulation of the Peace River has caused directional changes toward drier conditions in the PAD. Instead, evidence shows that climate and climate-driven changes in hydrology are the overwhelming drivers of hydroecological conditions in the PAD.
4. Paleolimnological records identify that the Athabasca Delta is highly responsive to changes in Athabasca River flow regimes. Yet, the Athabasca River and Delta have been largely understudied while attention over the past 40+ years focused on effects of changing Peace River discharge. Thus, there is a heightened need for policies that will ensure adequate downstream Athabasca River discharge and its important role in contributing positively to ecosystem integrity.
5. Climate changes over the past 1000 years have led to characteristic responses in the quantity and seasonality of streamflow generated at the headwaters of the Mackenzie River Basin. The hydrograph of the 20th century is unique compared with the past 1000 years. Continuing trends towards declining spring freshet and summer discharge reinforces the need for stringent allocation of freshwater resources for effective stewardship of downstream ecosystems within the Mackenzie River Basin.
6. A 5200-year record of Lake Athabasca water-level variations reveals that society in western North America must now prepare for potential water scarcity of magnitude and duration not experienced since European settlement. Because water supply is declining as consumptive uses are rising, creative management strategies are urgently required to meet demands of multiple stakeholders.
Recommendations

We recommend that a lake hydroecological monitoring program be implemented as a priority item in the development of an ecosystem management plan for the PAD. In the face of rapid industrial, urban, and agricultural development, compounded by the effects of rapidly declining freshwater availability because of climate change, a monitoring program will provide knowledge of trends and status of hydroecological conditions into the future. Such knowledge will be necessary to develop guidelines for the allocation of upstream water resources and assess their effectiveness. Since hydrological processes are the main driver for alteration of ecological status in the PAD, a monitoring program must start with gathering information on hydrological variability. Our past research has shown that tremendous differences in hydrological conditions exist spatially across lakes of the delta. Therefore, the lake monitoring program must select informative sampling sites that span these gradients so that the data can be scaled-up to the entire delta. We propose that lake water samples be collected for analysis of water-isotope composition ($\delta^{18}O$, $\delta^{2}H$) because, as we have shown (Wolfe et al. 2005, 2007b, 2008b; Yi et al. 2008; Wiklund et al. 2012a), these tracers efficiently allow detection of the influence of precipitation (including distinction between snow and rain), river floodwaters, and evaporation on lake water balance at a landscape scale (e.g., Fig. 9). We propose that ~60 lakes and ~10 river sites or a representative subset (see Wolfe et al. 2007b) be sampled three times a year — soon after ice-off (early to mid-May), mid-summer (late July), and fall (mid-September) — to capture intra-annual variations in hydrological conditions. Brock et al. (2008, 2009) illustrates how water-isotope sampling over a 3-year period was used to identify spatial and temporal differences in the extent of river flooding and lake evaporation, and the main drivers in the patterns that emerged, based on data from the downstream Slave River Delta. There is much to be gained from a continuous long-term water-isotope sampling of representative lakes, especially when it is founded on the comprehensive knowledge that we have generated across multiple spatial and temporal scales. Without this knowledge, a new monitoring program would require many years to decades before trends are detected and thresholds are defined. But with the approach we advocate, data can become available immediately and in near real-time to inform management decisions. For example, these data will closely track evaporative drawdown of lakes that have not recently received floodwaters and identify when and where important thresholds are crossed. Water-isotope tracer sampling could readily tie into other monitoring approaches of river flooding extent (e.g., remote sensing) and be broadened to incorporate other limnological (e.g., water chemistry — see Wolfe et al. 2007b; Wiklund et al. 2012a) and ecological (e.g., epiphytic algae — see Wiklund et al. 2010) tracers of aquatic ecosystem integrity. For the above reasons, we recommend that these approaches be incorporated into Environment Canada’s new monitoring program currently in development for the lower Athabasca River (Environment Canada 2011).

Concluding comments

The Peace–Athabasca Delta is a dynamic floodplain landscape that responds sensitively to variability in climate and river hydrology, but effects of Peace River regulation at the WAC Bennett Dam that have long been presumed are not discernible in lake sediment reconstructions of past hydroecological conditions. Rather, the temporal perspective offered by multiple paleolimnological records, informed by contemporary process studies, suggests that the dominant current human perception of “normal conditions” in the PAD likely formed during the late 1800s and early 1900s. At this time, anomalously high Lake Athabasca water levels, in the context of the past 5200 years, were supported by increased river discharge. Inaccurate perception of normal conditions, combined with previous studies that relied upon data of insufficient duration and scope, have likely contributed to the incorrect paradigm that the delta is drying and dying by unnatural causes. To the contrary, the PAD continues to evolve as a natural floodplain landscape. But, climate change now threatens to lead to further drying. Our paleolimnological research of the past 12 years has provided new knowledge, including the key insight of the pressing need for stringent water resource management informed by a comprehensive hydroecological monitoring program. This will effectively guide and evaluate the performance of upstream water resource allocation policy to ensure environmental flows into the future. Notably, our research has demonstrated that the PAD is an important regional bellwether, warning of imminent reductions in freshwater availability for societies and ecosystems in western North America reliant on high-elevation runoff — a finding that demands the attention of leaders tasked with managing our water resources.

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