Bi-directional hydrological changes in perched basins of the Athabasca Delta (Canada) in recent decades caused by natural processes

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Keywords: paleolimnology, Peace-Athabasca Delta, loss-on-ignition, hydrological change, natural avulsion, perched basins, Wood Buffalo National Park Action Plan

Supplementary material for this article is available online

Abstract

[1] Previous studies of river hydrometric records and Indigenous Knowledge holders claim that flood-induced recharge of ecologically important perched basins decreased across the Peace–Athabasca Delta after 1968 due mainly to hydroelectric regulation of Peace River flow. Natural deltaic processes and climate are acknowledged as additional, lesser contributors, but are challenging to evaluate. We use sediment records spanning ~115 years from nine perched basins across the Athabasca Delta to test if unidirectional drying coincides with river regulation. Results show bi-directional hydrological changes since the early 1980s, not 1968, to reduced flooding in areas east of the Embarras River confluence with Cree/Mamawi creeks and increased flooding northward along the Cree/Mamawi distributary. The timing and pattern pinpoint the 1982 Embarras Breakthrough, a natural avulsion that diverted flow northward and away from the Athabasca Delta terminus, as the principal cause. The results demonstrate the need to factor natural deltaic processes into impending decisions on the delta’s UNESCO World Heritage status and implementation of a federal Action Plan to mitigate widespread drying.

1. Introduction

[2] Many regions of western North America are experiencing decline of water supply and deterioration of ecologically- and culturally-important aquatic habitat, which is challenging the ability of society to respond effectively (Burn et al 2004, Déry and Wood 2005, Rood et al 2005, Schindler and Donahue 2006, Barnett et al 2008, Sauchyn et al 2015, Scalzitti et al 2016). This is a focal point for the Peace–Athabasca Delta (PAD), the world’s largest freshwater boreal delta. Located at the confluence of the Peace and Athabasca rivers in northern Alberta (Canada; figure 1), this ~6,000 km² delta provides important habitat for waterfowl, wood bison and other wildlife, and holds traditional importance to the First Nation and Métis communities of the region. Consequently, it is recognized as a Ramsar Wetland of International Importance and contributes significantly to Wood Buffalo National Park’s designation as a UNESCO World Heritage Site (Timoney 2013). Despite efforts of federal (Parks Canada, Environment and Climate Change Canada), First Nation (Athabasca Chipewyan and Mikisew Cree) and Métis, provincial (Alberta) and international agencies (UNESCO, Ramsar Convention) to preserve this world-renowned floodplain landscape, concerns have persisted for over 60 years about water-level declines and deterioration of aquatic habitat. Concerns center on the abundant, ecologically important, shallow, perched basins (i.e., restricted- and closed-drainage lakes) within the delta that are prone to drying and then refill...
3 While there is broad consensus that water levels have been declining in many areas of the PAD during recent decades, the primary cause(s) remain controversial (IEC 2018). On one side, Indigenous knowledge holders and reports by scientists and consultants claim that decline of water levels and ice-jam flood induced recharge of the perched basins throughout the PAD began after 1968, due primarily to hydroelectric regulation at the headwaters of the Peace River (PADPG 1973; Prowse and Conly 1998, 2002, Prowse et al 2006, Dubé and Wilson 2012, Beltaos 2014). The scientific studies are based mainly on analyses of hydrometric records available since the 1950s at a few locations upstream of the PAD in the Peace River. This perspective has gained considerable traction in recent years. In 2014, the Mikisew Cree First Nation (MCFN) petitioned WHC/IUCN to designate Wood Buffalo National Park as ‘World Heritage in Danger’ based, in large part, on claims that ‘dam-induced changes to the Peace River have resulted in a severe deterioration of the PAD’s main recharge mechanisms’ (MCFN 2014, p 18). This claim was also advanced in the subsequent WHC/IUCN Reactive
Monitoring Mission in response to MCFN (2014): ‘Regulation of the Peace River… along the upper reaches in British Columbia is widely accepted as a continual and significant threat to the PAD’ (WHC/IUCN 2017, p 17) and, based on traditional knowledge, in the ensuing Final Report of the Strategic Environmental Assessment: ‘the PAD as a whole is drying, and that this drying has coincided with BC Hydro regulation of the Peace [River]’ (IEC 2018, p 5–19). These statements imply that Peace River regulation has caused widespread unidirectional change towards less frequent flooding and drying of perched basins across the entire PAD starting after 1968.

[4] On another side, longer temporal data (decades to several centuries) and broader spatial perspectives provided by paleoenvironmental research (e.g., analyses of lake sediment cores and tree-ring records), supported by historic maps and compilations of human observations of ice-jam flood events, identify that trends of declining river flow, lower delta water levels, reduced flood frequency (Wolf et al 2006, 2008a, Sinnatamby et al 2010, Sauchyn et al 2015) and directional change to drying of perched basins in the northern Peace sector of the delta (Wolfe et al 2005, 2008a, Sinnatamby et al 2010) did not coincide with river regulation. Instead these records indicate that drying began several decades before hydroelectric regulation and initiation of the Peace River hydrometric records. These findings support conclusions that climatic processes exert overwhelming control on hydrological recharge and water balance of the perched basins, not river regulation (Wolf et al 2012). In the southern Athabasca sector of the PAD, analyses of sediment records from three perched basins identified two geomorphic events, which modified flow paths of the Athabasca River and its distributaries, as the main causes of hydroecological changes during the past century: one engineered in 1972 (Athabasca River Cutoff) and the other a natural avulsion in 1982 (Embarras Breakthrough; also referred to as Cree Creek Avulsion by Timoney 2013) (Wolf et al 2008b). One of the lakes situated along Cree/Mamawi creeks became more flood-prone after the Embarras Breakthrough event directed increasing flow from the Athabasca/Embarras river network northward toward this lake. It also re-directed river flow away from another lake located east of the Embarras Breakthrough, which subsequently became less flood-prone. A synthesis of the paleoenvironmental studies in the PAD concludes that roles of climate and natural deltaic processes have been underestimated by the other knowledge sources, because these processes operate over broader scales of time and space than captured by available river hydrometric records and observations of land users (Wolf et al 2012).

[5] Although speculated upon, the Wolf et al (2008b) study does not include sufficient spatial coverage to determine if widespread drying of perched basins across the Athabasca Delta is due to the 1982 Embarras Breakthrough, or, as widely claimed, to initiation of hydroelectric regulation of the Peace River in 1968. Here, we test these competing hypotheses. Based on prior studies that have identified increases in whole-lake production and sediment organic matter content in response to decline of flood frequency (McGowan et al 2011), we use loss-on-ignition analyses of radiometrically-dated sediment cores from nine flood-susceptible perched basins along an ~67-km transect (river distance) across the entire Athabasca Delta to reconstruct hydrological conditions during the past ~65–115 years. This includes the terminal region of the Athabasca River that encompasses the Athabasca Chipewyan First Nation traditional territory (Indian Reserve 201) downstream of the Embarras Breakthrough.

2. Study area

[6] The Athabasca Delta is the largest (~1,970 km²) and most active of the three deltaic regions that make up the PAD, which also includes the relic Peace Delta to the north (~1,680 km²) and smaller Birch Delta to the west (~170 km²; PADPG 1973; figure 1). The Athabasca and Peace deltas have contrasting river hydrology. Under normal flow conditions, tributary channels in the Peace Delta convey water that drains northward out of the PAD towards the adjacent, lower-elevation Peace and Slave rivers. During the spring freshet (late April to early May), episodic ice-jams events develop on the Peace River that persist for a few hours to a week or so in duration and can raise the Peace River sufficiently to cause southward flow reversals and overland flooding in the Peace Delta that can replenish the perched basins.

[7] The Athabasca River flows directly into the Athabasca Delta and divides into a number of smaller distributaries that flow north- and eastward towards the Athabasca Delta terminus where flow enters Lake Athabasca. Lakes in the Athabasca Delta can receive river floodwater during both spring ice-jam events and the open-water season. During the past 45 years, both engineered and natural changes to river channels have altered the distribution of river flow in the Athabasca Delta. In 1972, the Athabasca River’s impeding avulsion into the Embarras River channel (a major distributary of the Athabasca River) was prevented by engineered excavation of a channel across a tight bend in the Athabasca River to maintain the navigable route for river barges and avoid redirection of river flow away from the terminus of the Athabasca River, including Athabasca Chipewyan First Nation traditional lands. Ten years later, in 1982, a natural avulsion of the Embarras River (the ‘Embarras Breakthrough’; figure 1) began to divert substantial and increasing flow northward via Cree and Mamawi creeks towards the large, central open-drainage Mamawi Lake and away from the terminus region and Indian Reserve...
where Athabasca and Embarras river flow enters Lake Athabasca. Estimates from soon after the natural avulsion suggested that the Embarras Breakthrough directs 58% of Embarras River discharge (3%–8% of Athabasca River mainstem flow) northward along Cree and Mamawii creeks and nearly doubled the inflow to Mamawii Lake, values that have been increasing ever since (De Boer et al. 1994, PADTS 1996, Timoney 2013).

3. Methods

[8] Water balance of the numerous shallow, perched basins is controlled by variations in flux of input waters (river floodwater, precipitation) and evaporative losses. Previous studies have demonstrated groundwater does not substantially influence water balance of the delta’s perched basins (PADPG 1973, Prowse et al. 1996). River floodwater, laden with inorganic sediment, provides an important source of inflow to these lakes, a record of which is preserved in their stratigraphic profiles (e.g., Wolfe et al. 2006). Flooding results in relatively high lake sediment inorganic matter content and low organic matter content due to influx of suspended mineral sediment carried by the rivers and suppression of aquatic plant production by increased water-column turbidity (Wiklund et al. 2010, McGowan et al., 2011, Wiklund et al. 2012). When lake flooding is reduced, sediment organic matter content increases due to higher in-lake production of algae and aquatic plants and lower input of mineral sediment. We use measurement of organic and inorganic matter content profiles in sediment cores by loss-on-ignition methods to determine periods of increased or decreased flooding at nine shallow perched basins along an ~67 km transect (river distance) across the Athabasca Delta. Three lakes (PAD 76 [58° 31.386’ N, 111° 32.294’ W], 30 [local name: Mamawii Pond; 58° 30.605’ N, 111° 31.025’ W] and 31 [Johnny Cabin Pond; 58° 29.763’, N 111° 31.101’ W]) are located along Embarras Creek north of the Embarras Breakthrough and six lakes (PAD 32 [58° 29.838’, N,111° 26.592’ W], 26 [58° 25.192’ N, 111° 16.171’ W], M2 [Marta’s lake; 58° 25.099’ N, 110° 54.823’ W], M5 [Lake South of Tokyo Sney; 58° 30.149’ N, 110° 47.585’ W], M7 [Ross’s Corner; 58° 26.172’ N, 111° 02.801’ W] and 71 [58° 33.441’ N, 110° 52.531’ W]) are located east and northeast of the Embarras Breakthrough and span the distance to the terminus of the Athabasca River (figure 1).

[9] Sediment cores were collected from the lakes in 2010 (PAD 31), 2015 (PAD M5, M7, 26, 32), 2016 (PAD 30, M2), 2017 (PAD 71) and 2018 (PAD 76) using a gravity corer (Glew 1989) operated from a small boat or pontoon of a helicopter. Sediment cores were described and sectioned within 24 h of collection into 1-cm intervals at a field base in Fort Chipewyan. Once sectioned, the samples were kept refrigerated (4°C) and in the dark until analyzed at University of Waterloo.

[10] Sediment cores were dated using gamma-ray spectrometric measurement of 210Pb and 226Ra (via daughters 214Pb and 214Bi) activity at alternating 1-cm interval throughout the upper ~20–40 cm of each core. For each sample, 2–4 g of freeze-dried sediment was packed into pre-weighed tubes to 35-mm height. A silicone septum and 1 ml of 2-ton clear epoxy were placed on top of the sediment, and 228Ra and its decay products (224Pb and 214Bi) were allowed to reach equilibrium with parent isotope 226Ra for at least three weeks before measuring activity. Samples were run for 23–95 h at the University of Waterloo’s WATER Lab Ortec co-axial HPGe Digital Gamma Ray Spectrometers interfaced with Maestro 32 software. For individual cores, total 210Pb activity ranged 0.03–0.17 Bq g⁻¹ and background 210Pb activity was 0.03–0.05 Bq g⁻¹. Background depth was determined where total 210Pb activity equals supported 210Pb (= 226Ra) activity when accounting for their pooled measurement uncertainty (Binford 1990). The Constant Rate of Supply (CRS) model was used to calculate 210Pb-based ages and sedimentation rates (Appleby 2001, Sanchez-Cabeza and Ruiz-Fernandez 2012). The reference accumulation rate approach was utilized (see Appleby 2001, Eq. 34) ensuring complete integration of the unsupported 210Pb inventory. Dates below the unsupported 210Pb horizon were extrapolated based on the mean dry mass accumulation rate during the 210Pb-dateable portion of the records.

[11] Subsamples of ~0.5–1 g wet mass from each 1-cm sediment interval were analyzed for moisture, organic matter, and carbonate content by weight loss on heating at temperatures of 90 °C (24 h), 550 °C (2 h), and 950 °C (2 h), respectively (Heiri et al. 2001). Mineral matter content was determined as the sediment mass remaining after final heating to 950 °C, and inorganic matter content as the sum of mineral plus carbonate contents.

Organic and inorganic matter contents are expressed as a percentage of total dry sediment mass. Results are reported for the post-1900 intervals of the sediment cores.

4. Results and Interpretation

[12] 210Pb activity profiles in sediment cores from the six perched basins located east and northeast of the Embarras Breakthrough (PAD 32, 26, M7, M2, M5, 71) and PAD 76, located north of the Embarras Breakthrough and partially sheltered by trees and shrubs, show a relatively consistent pattern of low values near the base and marked rise towards the top of the cores, punctuated by occasional variability likely caused by episodic input of flood-supplied sediment with low 210Pb activity (figure 2). Background 210Pb activity was
reached between 7 and 39 cm depth, indicating variability in sedimentation rates among these lakes. In contrast, sediment cores from the other two perched basins located north of the Embarras Breakthrough show markedly different $^{210}\text{Pb}$ activity profiles, with low activity near the base of the cores, a rise to peak activity at mid-depths, and sharp decline in upper sediments (above 6 cm in PAD 30, 16 cm in PAD 31). The decline of $^{210}\text{Pb}$ activity in upper sediments coincides with a substantial rise in inorganic matter content of sediment and date to the early to mid-1980s (figure 3). Despite challenges of dating cores by $^{210}\text{Pb}$ methods in dynamic sedimentary environments such as these floodplain lakes, accuracy of our established chronologies can be demonstrated through repeated, consistent dating of the clearly visible contact between overlying light-grey inorganic-rich sediment on top of deeper black organic-rich sediment at ~1982 in cores collected from PAD 31 in 2001 and 2010 (figure 3).

[13] The stratigraphic profiles of organic and inorganic matter content demonstrate two patterns of temporal change in flood influence in the study lakes with respect to flow re-routed by the Embarras Breakthrough after 1982 (figure 4; tables S1–S9 is available online at stacks.iop.org/ERC/1/081001/mmedia). Prior to 1982, sediments at PAD 30, 31 and 76, located north of the Embarras Breakthrough, possess relatively high organic matter content (25%–55%) compared to the other six perched basins located east and northeast of
the Embarras Breakthrough, suggesting PAD 30, 31 and 76 were less frequently flooded. After 1982, inorganic matter content increased markedly at PAD 30 and 31 to 80%–90%, identifying a change to more frequent input of mineral sediment by river floodwaters. These results are consistent with prior multi-proxy analyses of a sediment core from PAD 31 (Wolfe et al. 2008b). At PAD 76, the rise of inorganic matter content was more gradual and delayed. In contrast, sediment cores from five of the six perched basins east and northeast of the Embarras Breakthrough (PAD 32, 26, M5, 71) show the opposite pattern. High inorganic matter content (>90%) occurs prior to 1982, indicating frequent, strong influence of river flooding, and organic matter content increases after 1982, signalling that flood influence declined. Rising organic matter content began several years after 1982 in some of these lakes (e.g., ~1990 at PAD 32, 26, M5), which is consistent with knowledge that continual bank and river erosion at the site of the Embarras Breakthrough has increased capture of Athabasca and Embarras river flow by Cree and Mamawi creeks over time since 1982 (Timoney 2013). The resulting gradually increasing northward flow over time, and the more sheltered location of PAD 76, also likely explains the delayed post-2000 response to increase in river floodwater influence at this lake. Sediment composition did not change noticeably at PAD M2 after 1982, whereas organic matter content increased after ~1930 at several of
the study lakes (PAD 76, 30, 31, 32, M7 and M2; figure 4). However, sediment cores from all nine study lakes show no directional change towards less frequent flooding coincident with Peace River regulation since 1968. Indeed, the only change recorded at 1968 in any of the nine lake sediment records is a short-lived increase of inorganic matter content at PAD M2 during ~1965–1974, which is interpreted to indicate increased flooding to this lake during this interval. We considered other possible mechanisms to explain the organic matter profiles, such as diagenesis which commonly leads to down-core decline of organic matter content, but this cannot explain the profiles at PAD 30, 31 and 76, because organic matter content shows the opposite pattern. For the other lakes, given their variable sedimentation rates, diagenesis is highly improbable as a mechanism that could produce the temporally consistent increase in organic matter content after 1982.

5. Discussion

[14] In large, complex freshwater landscapes, recognition of the relative roles of anthropogenic and natural influences on hydrological conditions requires sufficient spatial and temporal perspectives. However, these data are rarely available because comprehensive long-term monitoring programs are often absent, or sampling locations are too sparse and records do not extend long enough to characterize reference conditions. In such situations, paleolimnological studies have long been used to reconstruct pre-disturbance conditions and identify the timing and cause(s) of environmental change (e.g., Smol 1992, Smol 2008, Wolfe et al 2008b, Lintern et al 2016, Gell 2017).

[15] Among the potential drivers of hydrological change in the Athabasca Delta, the Embarras Breakthrough is rarely mentioned or omitted in recent assessments (Beltaos 2014, MCFN 2014, 2016, WHC/IUCN 2017, IEC 2018), despite prior evidence of its hydrological effects (Wolfe et al 2008b, Timoney 2013). Results from the present study substantially expand upon the spatial coverage in Wolfe et al (2008b) and demonstrate clear evidence for the Embarras Breakthrough as the major driver of hydrological changes for perched basins across the Athabasca Delta. The Embarras Breakthrough directed Athabasca River flow, via the Embarras River, into Cree and Mamawi creeks and the low-lying central region of the PAD, which has led to more frequent flooding in a small, central region of the PAD (PAD 30, 31 and eventually PAD 76). Conversely, flood influence has declined since 1982 at the perched basins located to the east (PAD 32, 26, M7) and in the northeastern Athabasca River terminus region (PAD M5, 71). An exception is PAD M2, which has remained strongly flood prone due to its proximal location to a sharp bend in the Athabasca River. Based on the organic and inorganic matter stratigraphic profiles from the perched basins along a ~67 river–km transect, the naturally occurring shift in distributary flow caused by the Embarras Breakthrough is the most influential hydrological change to occur during the past 115 years, consistent with findings of Wolfe et al (2008b).

[16] Declining Athabasca River discharge has been well documented (e.g., Schindler and Donahue 2006, Wolfe et al 2011, Wolfe et al 2012, Sauchyn et al 2015) and is evident in lakes of the Athabasca Delta as rising organic matter content after ~1930 in sediment cores from five of the nine lakes in this study (PAD 76, 30, 31, 32, M7). But, the rapid (PAD 30, 31) and gradual (PAD 76) decreases in sediment organic matter content after 1982 resulting from increased flooding caused by the Embarras Breakthrough has more than offset the effects of declining Athabasca River flow along Cree/Mamawi creeks. For lakes in the downstream terminus region of the Athabasca Delta, pronounced drying of perched basins is interpreted to be the consequence of subsequent diversion of river flow away from this region by the Embarras Breakthrough superimposed upon the reduction of Athabasca River flow as a result of climate change. Clearly, perched basins in the Athabasca Delta have entered a new hydrological regime, one characterized by bi-directional change to drying in areas east and northeast of the Embarras Breakthrough and wetting to the north along the Cree and Mamawi creek corridor.

6. Conclusions and implications

[17] Our study demonstrates the critical role of the 1982 Embarras Breakthrough on distribution of floodwaters conveyed by the Athabasca and Embarras rivers and bi-directional hydrological changes to perched basins across a substantial portion of the Athabasca Delta. This natural river avulsion led to increased flooding of perched basins to the north along Cree and Mamawi creeks and reduced flooding to the east toward the Athabasca River terminus. Hydroelectric regulation of Peace River flow since 1968 could not have produced these patterns of hydrological change. Correct identification of the major factors causing the drying of the delta’s perched basins, which lie at the center of concerns for deterioration of wildlife habitat and cultural land use, is important to inform impending decisions regarding designation of Wood Buffalo National Park as ‘World Heritage in Danger’ (WHC/IUCN 2017), and initiatives to protect the integrity of the PAD and its Outstanding Universal Values (WBNP 2019). For example, recommendations to mitigate presumed impacts of the WAC Bennett Dam on perched-basin hydrology in the Athabasca Delta by modifying the dam’s operating regime may be largely
unsuccessful if the dam has not led to lake drying. The approaches used in this study are readily transferable to other complex, water- and lake-rich landscapes where causes of hydrological change are difficult to decipher.

Acknowledgments

This research was supported by the Natural Sciences and Engineering Research Council (NSERC) Discovery and Northern Research Supplement programs to RH and BW, the Polar Continental Shelf Program and the Northern Scientific Training Program. Logistical support was provided by Wood Buffalo National Park. We thank Jelle Faber, Wynona Klement, Eva Mehler, James Telford and Morgan Voyageur for assistance during fieldwork.

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References

Appleby P G 2001 Chronostratigraphic techniques in recent sediments Tracking Environmental Change Using Lake Sediments: Basin Analysis, Coring, and Chronological Techniques (Developments in Paleoenvironmental Research 1) ed W M Last and J P Smol 1 (Dordrecht: Kluwer Academic Publishers) 9 171–2030–7923–6482–1
Barnett J, Lambert S and Fry I 2008 The hazards of indicators: insights from the environmental vulnerability index Annals of the Association of American Geographers 98 102–19
Beltoft S 2014 Comparing the impacts of regulation and climate on ice-jam flooding of the Peace-Athabasca Delta Cold Reg. Sci. Technol. 108 49–58
Binford B W 1990 Calculation and uncertainty analysis of 210Pb dates for PIRLA project lake sediment cores J. Paleolimnol. 3 53–67
Burn D H, Abdul Aziz O J and Pietroniro A 2004 A comparison of trends in hydrological variables for two watersheds in the Mackenzie River Basin Canadian Water Resources Journal 29 283–98
De Boer A, Winhold T and Garner L 1994 Embarras River Breakthrough to Mamawi Creek Canadian Water Resources Journal 19 35 D.2
Dery S J and Wood E F 2005 Decreasing river discharge in northern Canada Geophys. Res. Lett. 32 L1040
Dubé M G and Wilson J E 2012 Accumulated state assessment of the Peace-Athabasca-Slave River system Integrated Environmental Assessment and Management 9 405–25
Gell P 2017 Using paleoecology to understand natural ecological character in Ramsar wetlands Past Global Changes Magazine 25 86–7
Glew J R 1989 A new trigger mechanism for sediment sampling J. Paleolimnol. 2243–1
Hall R J, Wolfe B B, Winklind J A, Edwards T W D, Farwell A J and Dixon D G 2012 Has Alberta oil sands development altered delivery of polycyclic aromatic compounds to the Peace-Athabasca Delta? PLoS One 7 e46089
Heiri O, Lotter A F and Lemcke G 2001 Loss on ignition as a method for estimating organic and carbonate content in sediments; reproducibility and comparability of results J. Paleolimnol. 25 101–10
Independent Environment Consultants (IEC) 2018 Strategic Environmental Assessment of Wood Buffalo National Park World Heritage Site 1–561
Lintern A et al 2016 Sediment cores as archives of historical changes in floodplain lake hydrology Sci. Total Environ. 544 1008–19
McCowan S, Leavitt P R, Hall R I, Wolfe B B, Edwards T W D, Karst-Riddoch T and Vardy S R 2011 Interdecadal declines in flood frequency increase primary production in lakes of a northern river delta Global Change Biol. 17 1121–24
MCFN (Mikisew Cree First Nation) 2014 Petition to the World Heritage Committee requesting Inclusion of Wood Buffalo National Park on the List of World Heritage in Danger 1–18
MCFN 2016 Water is everything Prepared by the Mikisew Cree First Nations for the UNESCO World Heritage Site 1–24
Peace-Athabasca Delta Project Group (PADPG) 1973 Peace-Athabasca Delta Project Technical Report Peace-Athabasca Delta Technical Studies (PADTS) 1996 Final Report PADTS Steering Committee Fort Chipewyan Alberta 106
Prowse T D et al 2006 Climate change, flow regulation and land-use effects on the hydrology of the Peace-Athabasca-Slave system; findings from the northern river initiative Environ. Monit. Assess. 113 167–97
Prowse T D and Conly F M 1998 Impacts of climatic variability and flow regulation on ice-jam flooding of a northern delta Hydrol. Processes 12 5589–610
Prowse T D and Conly F M 2002 A review of hydroecological results of the Northern Basins Study, Canada River Res. Appl. 18 429–46
Prowse T D, Peters D L and Marsh P 1996 Modelling the water balance of Peace–Athabasca Delta perched basins Peace–Athabasca Delta Technical Studies National Hydrology Research Institute
Rood S B, Samuelson G M, Braatne J H, Gourley C R, Hughes F M and Mahoney J M 2005 Managing river flows to restore floodplain forests The Ecological Society of America 3 193–201
Sanchez-Cabeza J A and Ruiz-Fernandez A C 2012 210Pb sediment radiochronology; an integrated formulation and classification of dating models Geochim. Cosmochim. Acta 82 183–200
Sauchyn D J, St-Jacques J M and Luckman B H 2015 Long-term reliability of the Athabasca River (Alberta, Canada) as the water source for oil sands mining Proceedings of the National Academy of Sciences USA 112 12621–6
Scalzitti J, Strong C and Kochanski A 2016 Climate change impact on the roles of temperature and precipitation in the western US snowpack variability Geophys. Res. Lett. 43 5361–9
Schindler D W and Donahue W F 2006 An impending water crisis in Canada’s western prairie provinces Proceedings of the National Academy of Sciences, United States of America 103 7210–6
Sinnatamby R N et al 2010 Historical and paleolimnological evidence for expansion of Lake Athabasca (Canada) during the Little Ice Age J. Paleolimnol. 43 705–17
Smol J P 1992 Paleolimnology: an important tool for effective ecosystem management Journal of Aquatic Ecosystem Health 1 49–58
