Flood hydrology of the Peace-Athabasca Delta, northern Canada

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Abstract:
This study conducted a systematic examination of the flood hydrology of the Peace-Athabasca Delta (PAD), a complex and internationally important freshwater ecosystem located in northwestern Canada. Three distinct zones of floodwater origin within the PAD were discerned on the basis of the dominant hydrology and the topography represented by a digital-elevation model (DEM): (1) perimeter Peace Delta, (2) perimeter Athabasca Delta, and (3) central delta lakes. Analysis of the satellite image and DEM-derived flood maps of historically significant events, combined with field data of open-water and ice-influenced flood stages, revealed that ice-jamming was the most effective and likely the only mechanism capable of recharging the highly elevated perimeter areas in the Athabasca and Peace Deltas. This supports the conclusion of previous studies that used hydrometric data external to the delta to infer inter-delta flood conditions. By contrast, even the record open-water flow to the Peace Delta could not generate overbank flow. Hydraulic simulation of the naturalized system (no dam & no weirs) suggests that overbanking of the lower Peace River would have been a rare occurrence without the effects of regulation. Both ice-jam induced and open-water high waters were found to recharge perched basins in the Athabasca Delta. Enlargement of the central delta lakes beyond the shoreline was determined to be an effective flood mechanism for filling low to mid-elevation wetlands. Comparison of the observed and naturalized lake levels indicates that flow regulation of the Peace River and addition of the weirs on delta outflow channels has, depending on the year, led to an increase or a reduction in the annual maximum potential of inland flooding via lake expansion. Copyright © 2006 Crown in the right of Canada, and John Wiley & Sons, Ltd.

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INTRODUCTION
The Peace-Athabasca Delta (PAD) is one of the largest inland freshwater deltas in the world. Since the late 1960s, the hydrology of the PAD has been influenced by hydropower reservoir operations in the Peace River headwaters, retention weirs on delta outflow channels, and significant climate variability. Such changes are synergistically important to the vast number of the small wetlands perched (elevated) above the connected flow system where occasional floodwater inputs are required to maintain ponded water (Peters et al., 2006). A review of reports and journal articles (e.g. PAD-PG, 1973; Farley and Cheng, 1986; PAD-IC, 1987; Jaques, 1989; PAD-TS, 1996; NRBS, 1996; Prowse and Lalonde, 1996; Prowse et al., 1996; Prowse and Conly, 1998; Timoney, 2002) suggests that recharge of these basins results from high backwaters induced by ice-jams rather than from extreme open-water flows, and that a number of distinct flood regimes are present. Despite three decades of hydrological investigations, however, a comprehensive study that combines intra-delta hydrometric...
data and flood mapping has never been completed to properly establish the full range of flood conditions that affect this complex aquatic ecosystem.

The objective of this study, therefore, is to conduct a broad-scale examination of river and lake high waters generated under ice-jam and open-water conditions, and to evaluate their effectiveness in recharging perched basins in the PAD. 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. Consequently, this study focuses on the available satellite imagery and field hydrometric measurements of historically important extreme events, supplemented with information derived using a digital-elevation model (DEM) and a hydraulic model. To permit examination of delta water-level regimes without the effects of flow regulation, hydraulic modelling was employed to remove the effects of regulation and produce a naturalized (no dam and no weirs) water-level record. Inundation prior to and since regulation is assessed to 1996, a year that marked the resumption of large-scale flooding in the PAD.

STUDY AREA

The PAD (~6000 km²) is recognized as a wetland of international importance by the Ramsar Convention, and 80% of the area is protected within Wood Buffalo National Park, a UNESCO World Heritage Site (Figures 1 and 2). The PAD formed at the west end of Lake Athabasca and consists of three deltas. The Peace (1680 km²), Athabasca (1970 km²), and Birch (170 km²) Deltas enclose Lake Claire (~1200 km²) and Mamawi Lake (~170 km²). These lakes are linked to Lake Athabasca (7800 km²) by the Prairie River and Chenal des Quatre Fourches and drain into the Peace and Slave Rivers by the Rivière des Rochers, Revillon Coupé, and Chenal des Quatre Fourches. Drainage of the system is normally northward to the Slave River, but when the Peace River stage is higher than the level of the central lakes, typically during spring ice break-up and summer high discharge events, flow in the connecting channels reverses into the delta lakes (PAD-PG, 1973). The Peace River headwaters became regulated in 1968 with the completion of the W.A.C. Bennett Dam for the generation of hydroelectricity. Outflow control structures were added on the Rivière des Rochers and Revillon Coupé in 1975–1976 to counter decreased peak lake levels associated with storage of runoff in Williston Reservoir (PAD-IC, 1987).

The PAD contains more than 1000 small lakes and wetland basins (Jaques, 1989) that provide food and habitat for waterfowl, muskrat and bison (Townsend, 1984). Many of the basins are perched above the main flow system where surface water is replenished via overland flooding, and decreases in the ponded level are almost exclusively the result of evaporation (Peters et al., 2006). A description of the climatology, hydrology and ecology of perched basins is presented in Peters (2003); Peters et al. (2006).

HYDROMETRIC DATA AND ANALYSIS

Observed water levels

Hydrometric measurements on Lake Athabasca began in 1931, but it was not until the PAD-PG (1973) investigations that monitoring of the delta lake and channel levels was initiated in the early 1970s. The locations of hydrometric station data (Environment Canada, 1998a) used in this study are presented in Figure 2(a). High-water marks at these sites and in select perched basins were occasionally surveyed (PAD-PG, 1973; Giroux, 1997; T. Carter, personal communication; S. Flett, personal communication).

Naturalized water levels

Flow conditions that would have generated intra-delta levels without the influence of regulation are assessed by linking the Peace River model results from Peters and Prowse (2001) with the One-Dimensional (ONE-D) Hydrodynamic model of the PAD (Environment Canada and BC Environment, 1995). ONE-D is based on
Figure 1. (a) Major drainage basins of the Peace-Athabasca Delta system. Dark circles are locations of hydrometric stations. (b) Hydraulic network for the one-dimensional hydrodynamic model of the PAD. Black circles with white crosses are boundary nodes, empty circles are internal nodes, thick black lines are reaches connecting the nodes, and solid squares are climate stations.
Figure 2. Peace-Athabasca Delta: (a) hydrological features and locations of water levels stations (black circles), (b) 8 July 1999 Landsat TM image, and (c) digital-elevation model.
the gradually varied unsteady flow theory, and uses a finite-difference scheme for solving the Saint-Venant hydrodynamic equations for water level and flow (conservation of mass and momentum). Details about the numerical scheme that routes flow along mesh points interpolated from cross-section data representing the channels and lakes are given in Environment Canada and BC Environment (1995). As recommended by Leconte et al. (2001), a 30-min time step was used in the simulations to limit numerical instability by preventing hydrograph oscillations.

ONE-D was made operational for the PAD in the late 1970s by Sydor et al. (1979) and was subsequently used by the PAD-IC (Farley and Cheng, 1986), NRBS (Aitken and Sapach, 1994), and Leconte et al., (2001). Lake cross-sections, seasonal Manning’s $n$ calibrations (a stage dependent $n$ was used for the large rivers that control drainage of the system), outflow rating curves, and inflow data were upgraded for this study. The PAD model is defined by a series of cross-sections organized in reaches and nodes representing the major lakes and channels (Figure 1(b)).

The main inflow boundaries of the model are mean daily discharge in the Athabasca River below Fort McMurray, Birch River below Alice Creek, Peace River at Peace Point and Fond du Lac Rivers provided by Environment Canada (1998a). The outflow boundary is represented by a rating curve that describes a functional relationship between stage and discharge at Fitzgerald on the Slave River. At its peak coverage, nearly 90% of the total area measured at the outflow boundary was gauged. To close the water balance, runoff from unmonitored areas (i.e. surrounding Lake Athabasca and along Athabasca and Slave River reaches) was estimated by applying a scaling factor to a representative (based on basin area or flow comparison) gauged tributary. The majority of the Peace and Athabasca Deltas, as well as the north shore of Lake Athabasca, are composed of poorly drained terrain (e.g. wetland and bedrock) that are believed to produce little runoff. These areas were ignored in the overall water balance.

Full details of the calibration and verification of the model are found in Peters (2003). The $n$ values selected for the summer period are in line with those quoted for alluvial channels, natural rivers and floodplains, which typically vary from 0.017 to 0.100 (Chow, 1964). The $n$ values were held constant for the entire open-water period and monthly values were computed to account for changing ice conditions (0.030 in November, 0.028 in December, 0.018 in January, 0.015 in February, and 0.020 in March and April). On the basis of flow conditions (‘B’ for backwater influenced) reported in the HYDAT archive (Environment Canada, 1998a), an ice cover was applied over a one-week interval in the fall and removed in the spring over a similar interval. The reduction in hydraulic radius resulting from the growth of ice was mimicked by raising the hydraulic table elevations describing the cross-section by 0.92 of the measured layer of ice (M. Sydor, personal communication). Channel and lake ice thickness ranges from 0.2 m in November to over 1.0 m in March. These hydraulic adjustments were made on a monthly basis with averages based on ice measurements on the Peace River and Lake Athabasca (S. Flett, personal communication; M. Jones, personal communication).

Areal mean precipitation over the lakes was estimated using Environment Canada (1998b) climate station data near the lakes (Fort Chipewyan, Uranium City, and Stony Rapids) and the Theissen-weighted averaging method. Precipitation accumulated on the ice cover was applied to the lakes over a one-week interval in late April when the lakes started rising in response to snowmelt runoff. During the open-water season, the difference between precipitation and evaporation was added to Lake Claire and Mamawi Lake surfaces on a daily time step. No suitable evaporation estimates were available for the large, deep Lake Athabasca, and were thus computed as a residual of matching the simulated to the observed water level on Lake Athabasca.

Simulation of the naturalized system (no dam and no weirs) was achieved by removing the Revillon Coupé weir from the hydraulic network, changing algorithm coefficients replicating the Rivière des Rochers weir to those for the natural rapids (Environment Canada, 1991), and replacing the Peace River regulated with naturalized flows from Peters and Prowse (2001). Other boundary conditions, as well as the model calibrations and conditions influenced by the local climate were kept the same as in the initial model run. Although it was realized that the frequency of small to medium ice-jams may be different under a natural flow regime, their influence on delta water levels was considered to be small. The inability of the ONE-D to reproduce highly transient hydraulic conditions precluded analysis of flow regulation effects on ice-jam flooding. With the
exception of extreme years (e.g. 1990), most of the naturalized data are within the range of those encountered in replicating the observed hydrology. The naturalized water levels (1968–1996) are believed to be within similar accuracy as found for the observed system (i.e. \( \pm 0.20 \) m for open-water and can be \( > \pm 0.20 \) m for ice-covered conditions). Figures 1A and 2A in the Appendices, present observed and simulated water levels at key hydrometric sites for the years 1990 (regulated Peace River flow and delta weirs) and 1971 (regulated Peace River and naturalized rapids).

**Flood-extent mapping**

The areal extent of overland flow produced by a large-scale, ice-jam event was obtained by outlining surface water discerned by remote-sensing image analysis. A DEM of the PAD was used to estimate the areal extent of inundation corresponding to an open-water lake level when an event pre-dated satellite technology, a satellite was out of service, or the local atmospheric conditions precluded a clear satellite image (see Pietroniro *et al.* (1996, 1999) for a full discussion of the development and sources of error in the DEM). The DEM is at least as good as the 1:50 000 topographic maps, although the accuracy was improved with the addition of various ground surveys (e.g. \( >100 \) perched basins, survey lines, and Global Positional System points) and lake areas derived from satellite imagery at a range of water levels. Flood mapping via the DEM assumed an equilibrium water level, thus possibly omitting localized channel overflow in the perimeter deltas. Flood maps were corroborated with field observations and historical accounts whenever possible.

**RESULTS AND DISCUSSION**

**Flood-zones characteristics**

The small channel network and relief of the PAD is poorly understood owing to the flatness and hydrological complexity of this remote, nordic system. This has made it difficult to classify wetland and small lake basins according to flood stages, especially where the flood mechanism and origin of floodwaters can vary. Townsend (1972) made the first attempt at linking perched basins to the water level of the central delta lakes, but this approach ignored floodwaters emanating from the perimeter delta channels. In a subsequent attempt to map the entire delta environment, Jaques (1989) measured the total water-covered area by means of satellite imagery analysis and produced a series of contour intervals at various stages following the drawdown of a delta-wide inundation in the spring of 1974. There are two problems with Jaques’ approach: (1) it omits \( \sim 20\% \) of the delta area above the starting flood level and (2) floodwaters mask inter-basin/channel flow pathways. Prowse and Demuth (1996) produced a map of the major drainage classifications based on Jaques (1989), which divides the PAD into three categories of hydraulic connectivity to the main flow system: open-drainage, restricted drainage, and isolated (PAD-PG, 1973).

The DEM provides a useful spatial analysis tool for this study as it captures the major elevation contours of the entire PAD, but not the micro-relief (Figure 2(c)). Inspection of this figure shows that the lowest basins occur adjacent to the central delta lakes, with the topography gently rising inland. Highest elevations are found in the Peace Delta where most of the landscape is above 212 masl (zone F10 to L12 in the DEM). The Athabasca Delta lies largely below 212 masl (zone M5 to P7). Jaques (1989, 1990) estimated that 78% of the productive wetland habitat is located above \( \sim 209.5 \) masl. This value closely matches the DEM area with elevation connection and the spill elevation of \( >100 \) basins surveyed (Figure 3).

A number of flood regimes or zones are present within the PAD depending on elevation and origin of overland flow (e.g. floodwaters originating from the Peace River vs Mamawi Lake). On the basis of an examination of the DEM and dominant channel and lake hydrology, three main flood zones where overland flows originate were identified: (1) perimeter Peace Delta, (2) perimeter Athabasca Delta and (3) central delta lakes. The mean daily water level for the natural (1931–1967), regulated (1976–1996) and naturalized (1976–1996) hydrology are examined to characterize the two perimeter and inner delta flood regimes.
Perimeter delta zones. The channel hydrology of the northern perimeter of the PAD is represented by the gauge on the Peace River below Chenal des Quatre Fourches near Rocky Point (Figure 2(a)). Comparison of the regulated (1976–1996) and naturalized (1976–1996) data at this site revealed that the winter water levels were on average more than 1 m higher after the introduction of flow regulation to the system, and that the summer peak level was on average similarly lower (Figure 4(a)). Under both flow regimes, high-water events typically occur during late April to early May when snowmelt runoff from upstream tributaries is opposed by a breaking-up ice cover, and subsequently in June to July when large rainfall/snowmelt runoff passes through the delta channels. These two high-water periods also apply to the Athabasca Delta.

The channel hydrology of the southern perimeter of the PAD is represented by the gauge on the Athabasca River near Jackfish Creek (Figure 2(a)). Owing to poor ONE-D simulation in the mid-reach of this river (sometimes >1 m overestimated in the summer; likely due to the absence of Richardson Lake in the network), the naturalized long-term mean was estimated by a simple re-calculation process where the difference between the simulated regulated and the naturalized system was applied to the observed record (Figure 4(b)). The estimated difference between the regulated and naturalized channel levels was relatively minor (winter <0.3 m; summer ~0.1; within model error) at this reach of the Athabasca River, especially when compared to those on Peace Delta channels. The above results indicate that the influence of flow regulation decreases with distance from the Peace River.

Central delta lake zone. Examination of the averaged lake level data revealed that freeze-up levels were slightly higher after the introduction of hydroelectric operations and weirs to the system, and that there was less of a decline during the ice-covered period, leading to higher (~0.5 to 1 m) winter levels, except for Lake Claire (Figure 5). In addition, the timing of the peak lake level was delayed about 2 weeks and was slightly lower (~0.1 m) under the influence of regulation. The PAD-IC (1987) and (NRBS, 1996; Aitken and Sapach, 1994; Prowse et al., 1996) reported similar findings for hydraulic simulations up to 1990, but these studies did not include the observed natural flow period prior to 1968 in their comparisons. The Lake Athabasca water-level pattern for the pre-regulation regime was comparable to that of the naturalized regime. However, the 30 + years prior to 1968 experienced higher water levels throughout the year (i.e. >0.2 m average summer peak) than the period since, implying wetter conditions within the contributing basins.

Flood-event based study. The above examination of the mean daily channel and lake levels revealed that high water, as well as the influence of flow regulation, varies both spatially and seasonally within the delta.
complex. Overbanking of channel water onto perimeter delta areas is most likely to occur during the ice break-up and/or open-water periods. The expansion of the central delta lakes into contiguous wetlands is most probable during mid-summer. In spite of providing valuable information about the general hydrology of the three major zones of floodwater origin, inspection of averaged water levels did not reveal the potential extreme floodwater levels generated within the PAD by each flood mechanism.

NRBS (Prowse and Lalonde, 1996; Prowse and Conly, 1998) assessed the hydrometeorological conditions controlling ice-jam floods at Peace Point on the Peace River (Romolo et al., 2006a,b for the latest studies) and the magnitude of open-water flood flows upstream of the Peace Delta up to the year 1992. Similar work was conducted by Doyle (1987) for ice-jam events upstream of the Athabasca Delta near Fort McMurray. The PAD-IC (Farley and Cheng, 1986) and NRBS (Aitken and Sapach, 1994; Prowse et al., 1996) evaluated the averaged effect of flow regulation on peak lake levels up to the year 1990, but they did not analyse/discuss individual open-water, high-water events. Although the flood processes have been outlined by others, an examination of observed maximum water levels generated by ice-jam versus open-water flooding inside the PAD, as well as the spatial influence of each flood type, has never been conducted. The following analyses focus on the rare documented inundations of perched basins in the Peace and Athabasca Deltas from floodwaters originating from the perimeter delta channels and central delta lakes.
Historical flood events

Ice-jam floods. Gray and Prowse (1993) present a discussion on thermal and dynamic break-up types. The latter is characterized by a large flood-wave produced by the rapid melt of a deep snowpack, pushing and breaking the ice cover (increased resistance to flow), which may jam (reduction in channel cross-section) and temporarily raise the river stage. Figure 6 presents the maximum break-up backwater levels on the Peace River at Peace Point and the Athabasca River below Fort McMurray. The effectiveness of ice-jamming in producing extremely high backwaters with considerably less discharge than those generated under ice-free conditions was demonstrated by Prowse and Lalonde (1996) at the hydrometric station ~70 km upstream of the Peace Delta. Gauged levels at Peace Point, however, cannot be directly extrapolated to the main delta (Prowse et al., 2002). The opportune documentation of the 1974 and 1996 ice-jam inundation events provided the necessary onsite data to test this flood mechanism in the Athabasca and Peace Deltas. The 1996 event was the first major ice-jam flood in the Peace Delta in over 20 years. The extent of potential flooding during this event was enhanced by reservoir flow releases (Prowse et al., 2002), as was recommended by NRBS (1996).
when hydrometeorological conditions appear conducive to ice-jam formation in the lower river reach. The Athabasca Delta, which has received little attention, has been inundated more frequently and was inundated by ice-jamming 6 years prior to the 1996 event (Peters, 2003).

Figure 6. Annual peak water level versus discharge under break-up conditions: (a) Peace River at Peace Point (modified from Prowse et al., 2002) and (b) the Athabasca River just below Fort McMurray.
Perimeter delta zone floods

1996 event. Dynamic ice break-ups were recorded on 20 April below Fort McMurray on the Athabasca River and on 24 April at Peace Point on the Peace River. The ice cover jammed near Moose Island in the Peace River and progressed up the Chenal des Quatre Fourches to Dog Camp and down to the confluence with the Slave River (Giroux, 1997). Peace River backwaters flowed down the usually inactive Claire River, peaking at 215-25 masl on April 29 (T. Carter, personal communication; Figure 7(a)). The Peace River attained 214-18 masl near the Chenal des Quatre Fourches and 210-02 masl at the Rivière des Rochers (Giroux, 1997). Ice-jamming was observed on the lower Athabasca River in the meander downstream of the erosion control works and on the Embarras River below the breakthrough to Mamawi Creek (Giroux, 1997), producing a peak of 216-61 masl on the Embarras River below the divergence and 211-52 masl on the Athabasca River above Jackfish Creek (Environment Canada, 1998a) (Figure 7(b)). Locations of named places are shown in Figure 2(a).

The backwaters generated by above normal flows (Prowse et al., 2002) and ice-jamming during this event were sufficiently elevated to spill channel flow onto floodplains and spread (5–10 days) onto the landscape. Flood mapping based on a classified satellite image provided by Pietroniro et al. (1999) shows that a large portion of the PAD was inundated by the time the jams cleared in early May (Figure 8(a)). A large number of the elevated perched basins east of the Claire River were replenished for the first time in over 20 years (zone G11 to K12 in the DEM), such as Egg Lake and Basin 19 (Figure 7(c)). Most of the low-lying wetlands towards Mamawi and Richardson Lakes were also flooded (zone H5 to K6). Ground surveys were not available to confirm if the area north of Jackfish Creek was flooded (Chipewyan Indian Reserve; zone M5 to P7); Giroux (1997) mentioned that it received little, if any, water. As shown below, inundation of this lowland area happened in 1974 as a result of ice-jamming.

1974 event. On 20 and 22 April, dynamic break-ups were recorded on the Athabasca River below Fort McMurray and Peace River at Peace Point. Local residents recalled that flooding in the PAD commenced at the end of the month as a result of massive ice-jams extending from Rocky Point on the Peace River to ~20 km down the Slave River (Peterson, 1992). The large flows behind the jams produced backwaters of 215-46 masl on the Peace River below Chenal des Quatre Fourches (S. Flett, personal communication) and 210-96 masl at the confluence with the Rivière des Rochers on May 2 (Environment Canada, 1998a; Figure 9(a)). During this event, the Peace River enlarged from its normal within bank width of 0.5–1 km to more than 5–10 km wide floodplain (Figures 8(b) and 10(a)). Jams also occurred within the Athabasca Delta (Peterson, 1992), with a peak level of 211-97 masl (may be higher) reported on the Athabasca River above Jackfish Creek (S. Flett, personal communication) (Figure 9(b)). Over a period of 10–14 days (Peterson, 1992), overland sheet flow originating from the south and north perimeter delta channels spread to virtually all perched wetland areas of the PAD, including the most isolated basins not replenished by the smaller event in 1996, forming a single large lake (Thorpe, 1986). Drainage of the central delta lakes was delayed due to a temporary rock weir at the outflow of Mamawi Lake (Figure 9(c)), which was partially washed away and removed the following year.

1996 versus 1974 event. A number of key factors combined to divert greater volumes of channel water onto the perimeter landscape and central delta lakes in 1974 than in 1996. Firstly, a jam on the Slave River severely restricted outflow from the system. Secondly, peak backwaters on the Peace River attained higher levels and were driven by greater discharges (Figure 6). Finally, overland flow lasted several days longer in 1974. This event was considered representative of the largest possible areal extent of inundation.

The flood episodes examined in this study, which are comparable to others described in the pre-regulation historical accounts (e.g. 1963; Peterson, 1995), occurred despite changes to the winter flow regime from hydroelectric operations in the Peace River headwaters (Prowse and Conly, 1998; Peters and Prowse, 2001). Statistical analyses by Timoney (2002) suggest that the frequency of ice-jam floods in the Peace Delta had
Figure 7. Water levels along (a) Peace River, (b) Athabasca River, (c) within inland basins, and (d) on the delta lakes in 1996 (Figure 2(a) for location of gauges)
Figure 8. Estimated extent of inland flooding (dark grey) as a result of ice-jams: (a) 1996 based on 18 May Radarsat SAR combined with 23 May SPOT multi-spectral classified imagery provided by Pietroniro et al. (1999) and (b) 1974 based on unclassified Landsat MSS images on 4 and 22 May.

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not significantly changed after 1968, and that the long-term (1826–1997) recurrence interval was about 1 in 6 years. Prowse and Conly (1998) concluded that the lack of large ice-jam flood events between 1972 and 1996 seemed to be related to a combined effect of climate variations and flow regulation. The degree to which flow regulation has potentially affected the generation of ice-jam flood events requires numerical
ice-jam modelling such as that developed by Beltaos (2003), but it still requires functional integration into the ONE-D Hydrodynamic Model of the PAD.

Overall, the two case studies examined in this study demonstrate that the generation of large ice-jam floods is an effective mechanism for replenishing the most elevated (i.e. >214 masl) perched basins within both the Athabasca and Peace Deltas. This supports the conclusion of Prowse and Lalonde (1996) that was based on evidence at the Peace Point hydrometric data and supported by anecdotal information. The next step in the analysis is to ascertain whether or not high waters generated during the open-water season has a similar inundation potential in the PAD.

Open-water floods

Subsequent to the spring period, the PAD is again prone to flooding as a result of a large, rapid flood-wave travelling through the perimeter delta channels and the expansion of lakes beyond their main shoreline. For comparison to the break-up flooding examined earlier, the inundation potential under open-water conditions is demonstrated via the analysis of historical extreme events in the perimeter delta and central delta lake zones.

Perimeter delta zone floods

**Peace Delta.** Review of the Peace Point gauging station records (1959–1996), which was previously completed for the NRBS by Prowse and Lalonde (1996) for a time series several years shorter, revealed that the observed historical high flow on the Peace River occurred on 17 June 1990 (Environment Canada, 1998a; Figure 6(a)). The downstream water-level gauges were temporarily inoperational during the focal point of the flood-wave that progressed through the northern perimeter delta (Figure 11(a)). It was estimated through ONE-D simulations that the stage on the lower Peace River peaked (mean daily) on 17–18 June at 214-60 masl at the Claire River, 212-10 masl at the Chenal des Quatre Fourches, and 210-43 masl at the Rivière des Rochers confluence. This event, the highest open-water on record, temporarily caused flow reversal in the connecting channels (Peters, 2003), but as seen on the 29 June Landsat TM image (Figure 10(b)), no noticeable overbank flow into the river floodplain and adjacent wetlands took place. Moreover, ponded water observations in Egg Lake and nearby perched basins showed no floodwater inputs (S. Flett, personal communication) and historical accounts have no mention of flooding during that summer (Peterson, 1992, 1995). An additional 10 to 15% discharge would have been required to produce greater than bankfull conditions on the Peace River (PAD-PG, 1973). Analysis of the observed hydrometric record in the lower Peace River suggests that perched environments in the northern perimeter of the PAD (zone E11 to L12) are unlikely to be replenished by stormflow events generated by the Peace Basin. This supports the conclusion of Prowse and Lalonde (1996) that was based on upstream hydrometric data and anecdotal information.

It was estimated that by using the ONE-D model without the effects of flow regulation, the 1990 peak flood-wave would have been ~1 m higher than observed along the Peace River delta reach (Figure 11(a)). Given that such peaks exceed the flow range over which the hydraulic model was calibrated and verified, they may be less accurate than other naturalized water levels. Nevertheless, open-water peak stages of that magnitude, of which only the naturalized 1972 peak was comparable (Peters and Prowse, 2001), would likely have overflowed into the Peace Delta. Simulations using a more detailed 2-dimensional hydraulic model of the PAD are required to confirm this.

**Athabasca Delta.** Examination of the records from below Fort McMurray revealed that the observed historical high flow on the Athabasca River occurred on 15 July 1971 (1957–1996; Environment Canada, 1998a; Figure 6(b)). Upon reaching the delta, this stormflow overwhelmed levees of the Athabasca River near zone E3/E5 and caused erosion/transport of material towards the Embarras River (PAD-PG, 1973). Floodwaters likely breached the west-bank of the Embarras and spilled into the Mamawi Creek region (zone E5 to F5) because smaller flows in the following decade ultimately eroded the breakthrough channel (DeBoer et al., 1994). Downstream, the Athabasca River near Jackfish Creek, a mean daily peak stage of 212-07 masl...
was measured on 20 July (Environment Canada, 1998a) (Figure 11(b)). Most of the delta area north of this hydrometric site (zone N4 to P7) lies below this elevation and experienced localized flooding. Ambrock and Allison (1972), for example, reported that nearby South Egg Lake was recharged and peaked at 211-41 masl during that event. As observed for the Peace Delta, considerably more discharge is required to produce an open-water stage comparable to those influenced by ice-jamming in the Athabasca Delta channels (e.g. Figure 6(b)).
The Athabasca River basin is not significantly affected by water-works schemes and has on a fairly regular basis (estimated at 1 in 5 years) generated stormflows capable of overtopping the meandering channel levees (Peters, 2003). It was estimated through ONE-D simulations that lake backwaters under a naturalized scenario would not have influenced the peak flood-wave near Jackfish Creek because of a > 2 m difference between the two measurement points (Figure 11(b)). The low-lying northerly portions of the Athabasca Delta (zone I4 to P4) are likely affected by Lake Athabasca expansion and associate backwaters in the delta channels, especially during abnormally high lake levels.

Central delta lake zone floods

The central lakes are connected and generally reach similar peak levels during the summer, except for 1973 and 1974 when a test weir on the outflow channel of Mamawi Lake retained floodwaters. The gauge on Lake Athabasca at Fort Chipewyan was used as a flood level index on the central delta lakes because there is a water level record prior to the introduction of regulation to the system. Examination of the observed open-water data at this site (averaged over 3 days to alleviate wind effects) revealed that the maximum level ranged from a low of 208.69 masl in 1945 to a high of 211.32 masl in 1935 (Figure 12). These extremes occurred before the closure of the dam. Since then, the highest Lake Athabasca level for the period of analysis was in 1996. The 1935 and 1996 events were chosen to evaluate the potential flooding via lake expansion.
1996 event. Within months of the 1996 spring ice-jam flood, the PAD experienced a second episode of water spillage into inland areas. This occurred as a result of a unique circumstance. Williston Lake reservoir was lowered 3 m over a 6-week period in response to the discovery of a sinkhole in the crest of the Bennett Dam and wet hydroclimatic conditions in the contributing basins (Peters et al., 1999). Leconte et al. (2001), using ONE-D, estimated that the central lakes would have been almost 0.5 m lower under typical reservoir operations, but still an above average lake level. The sustained high discharges in the Peace River impeded outflow from and contributed some reverse flow to the large lake complex, raising Lake Athabasca by almost 1 m above the spring lake level to a peak of 210.45 masl on August 16 (Figure 7(d)). The DEM-derived flood map shows that at the observed flood level, the large central lakes expanded beyond their normal shorelines, engulfing large areas of low-lying wetland and inland lakes (Figure 13(a)). For instance, Jemis Lake and Basin 11 located next to the north shore of Mamawi Lake were recharged (Figure 7(c)). The flood map also shows that Lake Athabasca inundated a large portion of the Athabasca Delta north of Jackfish Creek. Overall, an estimated 55% of the inland basins were replenished with lake water as a result of this event (Figure 3). Perched-basin environments unaffected by lake expansion are located within both elevated perimeter delta areas. To replenish these highly isolated basins (e.g. Egg Lake and Basin 19) would require a considerably higher lake level (Figure 7(c)).

1935 event. The peak lake level on 14 July 1935 was almost 1 m higher than observed in 1996. Comparison of the DEM-derived flood maps presented in Figure 13 reveals that the central lakes extended considerably farther inland in 1935 than in 1996. Lake Athabasca enlarged up to Lake Richardson and merged with Mamawi Lake and Lake Claire, forming one large body of water that inundated ~80% of the basins. Lake expansion >10 km inland did not recharge the areas north of Baril Lake (zone F11 to L12) and south of the Embarras River (zone J4 to L4). Flooding of these isolated environments requires considerably more outflow constriction and river inflow to raise the lakes by an additional 2 m. Long-term (1810–1930) reconstruction of water level changes for Lake Athabasca by analysis of tree rings indicates that this has not happened in the last two centuries (Stockton and Fritts, 1973), and that the 1935 high is representative of the maximum areal extent of perched-basin inundation via lake expansion.
Figure 13. Estimated extent of inland flooding (dark grey) from the enlargement of the delta lakes in the summer of (a) 1996 and (b) 1935.

**Observed versus naturalized lake levels.** Annual summer peak water levels under a naturalized hydrology were extracted from the Lake Athabasca data simulated using the ONE-D hydrodynamic model of the PAD described earlier. The year-to-year pattern of the observed regulated water-level record is similar to that of the naturalized record ($r = 0.80$), suggesting that hydroclimatic conditions within the unregulated portions of...
the contributing basins have a strong control on summer lake levels (Figure 12). For example, above average flood levels (>209.55 masl) were attained in the 1970s, and below average levels occurred in the early 1980s regardless of flow regulation influence. Overall, the naturalized open-water peak levels on Lake Athabasca (1976–1996 mean 209.57 ± 0.41 masl) were not significantly (P > 0.05) greater than those observed under the regulated regime (1976–1996 mean 209.54 ± 0.38 masl). The simulation efforts of this study support the general conclusion by the NRBS (Aitken and Sapach, 1994) that the outflow control structures on the Revillon Coupé and Rivière des Rochers have restored near average peak lake levels. By comparison, peak Lake Athabasca levels prior to the introduction of regulation (1931–1967 mean 209.86 ± 0.61 masl) are significantly (P < 0.05) higher than in the period since, indicating that wetlands contiguous to the lakes were recharged more frequently and/or to a greater elevation via lake expansion during the 1930s to the 1960s; but not up to the elevation influenced by ice-jam conditions on the perimeter channels.

Generalized conclusions from averaged summer conditions can be misleading. In particular, the 1990 peak level simulated for a naturalized scenario was estimated to be ~0.4 m higher than the observed lake level, which can be important when considering the total area potentially inundated by lake expansion with higher water levels. For instance, the recharge frequency of Jemis Lake (spill elevation of 209-75 masl) was estimated to have occurred 1.6 times less often under the current flow regime. The comparison of the observed and naturalized water levels suggests that flow regulation has in some years increased and in other years reduced the maximum potential of perched-basin inundation via the lateral expansion of the central lakes. Although it was previously found by Prowse et al. (1996) that the addition of the weirs has been ineffective in restoring water to the highly perched basins, this analysis of historical high-water events further shows that these basins were not and are unlikely to be recharged by central lake expansion.

CONCLUSIONS

This study conducted a systematic examination of the flood hydrology of the PAD, a complex and internationally important freshwater ecosystem located in northwestern Canada. Floodwaters within the PAD were found to originate from three distinct zones: the northern and southern perimeter delta channels and the central delta lakes. The perimeter deltas of the PAD are influenced by channel high backwaters induced by ice-jamming and flood flows generated under open-water conditions. The relatively flat ecosystem is also influenced by inundation resulting from the lateral expansion of large central lakes during the summer, the combination of which can lead to spatially complex flood histories within the PAD.

Through the comparison of in situ hydrometric data and flood maps of historically significant flood events, this study tested and supported the conclusion of Prowse and Lalonde (1996) that ice-jamming is the most effective mechanism for producing extremely high backwaters capable of recharging perched basins, in particular the elevated region of the Peace Delta where productive wetlands are situated (i.e. >214 masl). As evidenced by the 1974 event, large ice-jam floods in chorus in both the perimeter deltas were capable of causing near delta-wide flooding.

By contrast, the historical high, open-water flow event generated by the Peace Basin was insufficient to cause greater than bankfull flow conditions within the Peace Delta, and is considered unlikely to do so under the current flow regime. Simulation of the naturalized water-level regime suggests that even without the influence of flow regulation, overflow of the lower Peace River would have been a rare occurrence during ice-free conditions. In comparison, the unregulated Athabasca Basin occasionally produced localized overland flow in the Athabasca Delta under both open-water and ice-jam conditions.

The lateral expansion of the central delta lake into inland areas was found to be a notable mechanism for replenishing the low to mid-elevation (<212 masl) contiguous wetlands. An important implication of flow regulation was, depending on the year, an increase or a reduction in the annual maximum potential flooding of the low-lying areas from the central delta lakes.
Following an extended period of significant drying, large portions of the PAD were rejuvenated in the mid-1990s by flood events during the spring break-up and summer periods. It is recommended that future investigation focus on understanding the role of the upstream basins in generating floodwaters under both ice-jam and open-water conditions. In addition, given the overwhelming importance of ice-jam flooding to the ecosystem health of this northern aquatic regime, anticipated changes to this flood mechanism should be assessed for future climate conditions.

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Figure A1. Observed, simulated and naturalized water levels at key hydrometric stations during the 1990 water year
Figure A2. Observed, simulated and naturalized water levels at key hydrometric stations during the 1971 water year