Tree-Ring Inferences on Water-Level Fluctuations of Lake Athabasca

David M. Meko

Abstract: Tree-ring data were analyzed for a long-term perspective on ecological and hydroclimatic variations on the Peace-Athabasca Delta (PAD). The ecosystem of this Ramsar Wetland of International Importance in northeastern Alberta is sensitive to fluctuations in water levels of the numerous lakes, channels and perched basins, and attention has been focused in recent decades on the possibility of deleterious effects from climatic change and regulation of the Peace River by W.A.C. Bennett Dam. A network of eight *Picea glauca* tree-ring chronologies was developed, time series features of growth variation were summarized, and the chronologies were applied in a regression model to reconstruct an annual time series of early summer (July 11 to 20) water levels of Lake Athabasca for the period A.D. 1801-1999. Though statistically weak (R^2 = 0.36), the reconstruction verifies adequately in cross-validation and is consistent with anecdotal written records of a dramatic decline in water levels in 1879-81. Correlation of reconstructed and observed water levels improves with smoothing. Gaussian smoothing (ten years and longer) identifies a major low centred on 1890. The differential growth responses among the sites as well as evidence from other tree-ring studies suggest the 1890 low was associated primarily with diminished Peace River flows. The 20th century is unusual in a long-term context for high-amplitude multi-decadal variations in tree growth and reconstructed water levels, but the timing of these more recent fluctuations appears unrelated to the building of the W.A.C. Bennett Dam. Further research is needed to better discriminate the tree-ring signal for lake-level variation from the signal due to localized precipitation.

Résumé : Les données de cercles d'arbres ont été analysées pour recevoir une perspective à long terme sur des variations écologiques et hydroclimatiques dans le Peace-Athabasca Delta (PAD). L'écosystème de ce marécage de Ramsar qui a de l'importance internationale dans le nord-est d'Alberta est sensible aux fluctuations dans des niveaux d'eau des nombreux lacs, des canaux et bassins perchés, et dans les décennies récentes, on s'est concentré sur la possibilité des effets nuisibles de changements climatiques and de la regulation de la rivière Peace par le barrage W.A.C. Bennett. Un réseau de huit chronologies de cercles d'arbres Picea glauca a été développé, le résumé des caractéristiques de la séquence de temps en ce qui concerne la variation de croissance a été fait, and les chronologies ont été appliquées dans un modèle de regression pour reconstruire une séquence de temps annuelle des niveaux d'eau du Lac Athabasca au début de l'été (11-20 juillet) pour la période 1801-1999 apr. J.-C. Bien que cette reconstruction soit statistiquement

David M. Meko[1]

[1] Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ 85721

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faible ($R^2 = 0.36$), elle se vérifie suffisamment par contre-vérification, et elle conforme aux rapports du déclin dramatique des niveaux d'eau en 1879-81. La correlation des niveaux d'eau reconstruits et observés s'améliore avec lissage. La lissage Gaussian (10 ans ou plus) identifie un bas majeur qui se concentre sur l'an 1890. La réponses de croissance différentielle parmi les sites aussi que la preuve d'autres études de cercles d'arbres semble indiquer que le bas en 1890 était principalement associé avec l'écoulement diminué de la rivière Peace. Le 20e siècle est peu commun dans un contexte à long terme pour des variations de croissance d'arbres de grande ampleur parmi de nombreux siècles et pour des niveaux d'eau reconstruits, mais l'occurrence de ces fluctuations plus récents semble sans rapport avec la construction du barrage W.A.C. Bennett. Il est important de rechercher ce phénomène dans plus de détail pour mieux différencier le signal des cercles d'arbres pour le changement du niveau des lacs et le signal qui vient de la précipitation locale.

Introduction

The Peace-Athabasca Delta (PAD), a Ramsar Wetland of International Importance (http://www.ramsar.org/) located at the confluence of the Peace and Athabasca Rivers in northeastern Alberta, Canada, is the largest boreal freshwater ecosystem in the world (Peters and Prowse, 2001). The seasonal and interannual fluctuations of water levels are an essential component to the health of this ecosystem (Timoney, 2002). The regime of water-level fluctuation on the Peace River was permanently altered beginning in 1968 with the closure of the gates of the W.A.C. Bennett hydroelectric Dam (Bennett, 1970). Observations of water level decline in the PAD after construction of the dam raised concerns about ecological impacts and led to construction of weirs on one of the main channels connecting the PAD with the Peace River (Peace-Athabasca Project, 1971). While the weirs were apparently effective in restoring summer open-channel water levels, long-term drying out of perched basins that rely on episodic flooding remained a problem (Timoney *et al.,* 1997). Attribution of cause is difficult in a dynamic system such as the PAD; however, despite observed changes, the PAD remains a relatively healthy ecosystem (Timoney, 2002). Moreover, multi-proxy paleolimnological evidence from a lake in the northern part of the PAD suggests that hydro-ecological conditions since 1968 have not varied outside the broad natural range of variability of the past 300 years (Wolfe *et al.,* 2005).

To identify anthropogenic impacts on the hydrology and ecology of the PAD, it is essential that we understand the natural range of variability of the hydrologic and ecological systems. Much attention has been focused on the effects of flow regulation on the hydrologic system of the PAD, but recent studies have emphasized climate variability as an additional important hydrologic stressor (Prowse and Conly, 2000; Wolfe *et al.,* 2005). The lack of long-term datasets is one of the impediments to understanding the role of climate variability in observed changes in the ecosystem (Timoney, 2002). Tree-ring studies can help rectify this problem by providing several centuries of annually resolved time series. The time series of growth variations are directly relevant to ecological variability inasmuch as the trees are a vital component of the ecosystem. If a sufficiently strong hydrologic signal can be demonstrated in the tree rings, the time series of growth indices routed through an appropriate reconstruction model are relevant to the long-term hydrologic variability. Tree-ring data have a long history of application to the augmentation of hydrologic records for studies of climate variation and water availability in the United States and more recently in Canada (Schulman, 1945; Stockton and Jacoby, 1976; Smith and Stockton, 1981; Meko *et al.,* 2001; Case and MacDonald, 2003; Bonin and Burn, 2005; Woodhouse *et al.,* 2006). As part of an early multidisciplinary effort to deal with observed environmental changes on the PAD (Peace-Athabasca Project, 1971), Stockton and Fritts (1973) reported that the growth of white spruce (*Picea glauca*) along the natural levees of the channels of the PAD is positively related to changes in water level of Lake Athabasca. They exploited the relationship to generate a 158-year reconstruction of lake level, but could not address post-dam variations in tree growth or water level as the dam was still in its initial filling stage when the tree-ring data were collected.

In 2001, the British Columbia Hydro and Power Authority (BC Hydro) commissioned a new tree-ring study including field collections and application of modern reconstruction methods to further delineate the natural long-term variability of tree growth and water levels. Objectives included increasing the robustness and length of the reconstructed water levels as well as testing for tree-ring signatures of the influence of the W.A.C. Bennett Dam. The study included field collections of *P. glauca* in the summer of 2001 and development of ring-width chronologies and time series of stable isotopes (carbon and oxygen) of wood cellulose in tree rings (Meko, 2002; final report available at http://www.ncdc.noaa.gov/paleo/recons.html). Climatic interpretation of the stable-isotope time series was not possible because of large tree-to-tree variability in the isotope ratios; only four trees were sampled, while diagnostic statistics (Wigley *et al.,* 1984) indicated a sample of ten to 20 trees is necessary to adequately summarize the common signal. This paper is restricted to a description and extended analysis of the ring-width portion of the study. Ring widths from the 2001 collection are merged with those from Stockton and Fritts (1973) and the resulting chronologies are applied to generate a reconstruction of annual variations in lake level for A.D. 1801-1999. The reconstruction is analyzed to place water-level fluctuations of the 20th century in a long-term perspective, to delineate periods of sustained hydrologic drought, and to identify possible differences in time series characteristics of tree-growth and water level before and after the construction of the W.A.C. Bennett Dam.

Hydrologic Setting

The hydrologic setting of the PAD is summarized by Prowse and Conly (2000) and Wolfe *et al.* (2005). The PAD occupies an area of 3,900 km^2 at the confluence of the Athabasca, Peace and Birch Rivers at the western end of Lake Athabasca in northeastern Alberta. The PAD consists of a complex of channels, lakes, ponds and perched basins in a landscape of extensive grasslands, marshes and meadows. The environment is mainly alluvial and, except for natural levees and bedrock islands, topographic relief seldom exceeds one metre above the surface of the major lakes (Prowse and Conly, 2000).

The total mean annual runoff to Lake Athabasca and the PAD is 45.0 billion m^3 (Peace-Athabasca Project, 1971) and includes contributions from a broad swath of the Canadian Rockies between 52° N and 58° N (Figure 1). The Athabasca River, with headwaters in the Rocky Mountains of Jasper National Park, and a mean annual discharge of 431 m^3/sec (13.6 billion m^3/year) at Athabasca, is the most important source of inflow to the PAD. The Athabasca is characteristic of rivers with substantial contribution from snowmelt in that flows are generally low in winter and high in spring and summer. Other rivers flowing into the PAD have much more evenly distributed monthly mean flows, less dominated by melting snowpack. The Peace River, with a mean annual flow of 1,826 m^3/sec (57.6 billion m^3/year) at the town of Peace River, can also contribute inflow to the PAD, but only during high-flow events, such as periods of high spring snowmelt or the breakup of ice jams (Prowse and Conly, 2000). On average, however, this annual inflow is only on the order of 1.2 billion m^3 (Peace-Athabasca Project, 1971). The ice-jam floods, which do not occur every year, can inundate large elevated portions of the PAD and recharge the numerous perched basins otherwise disconnected from the main channels. These occasional floods are vital to the ecosystems of the PAD (Timoney *et al.,* 1997).

Outflow from the PAD is northward to the Peace River through a series of channels over nearly flat terrain. Aside from the occasional contribution of inflow, the Peace River exerts control over the hydrology of the PAD by acting as a hydraulic dam and modulating the rate of outflow. This modulation depends on the relative water levels on the Peace River and the open water bodies of the PAD (Bennett, 1970; Prowse and Conly, 2000). For example, the estimated outflow during May and June of 1968, 1969 and 1970 —when Peace River flows were diminished due to filling of W.A.C. Bennett Dam—was estimated to be four to six times the mean outflow that occurred previously (Peace-Athabasca Project, 1971).

After receiving outflow from the PAD, the Peace River becomes the Slave River, flows northward to Great Slave Lake, continues northward as part of the Mackenzie River system, and eventually empties into the Beaufort Sea.

Local precipitation is a relatively small component of the water balance of the PAD. Precipitation averages 391.7 mm annually at Ft. Chipewyan, with about 59 percent falling as rain in May to September (Wolfe *et al.,* 2005). This amount of precipitation is equivalent to an annual volume input of 1.52 billion m^3 or about 3.4 percent of the mean annual runoff to the PAD.

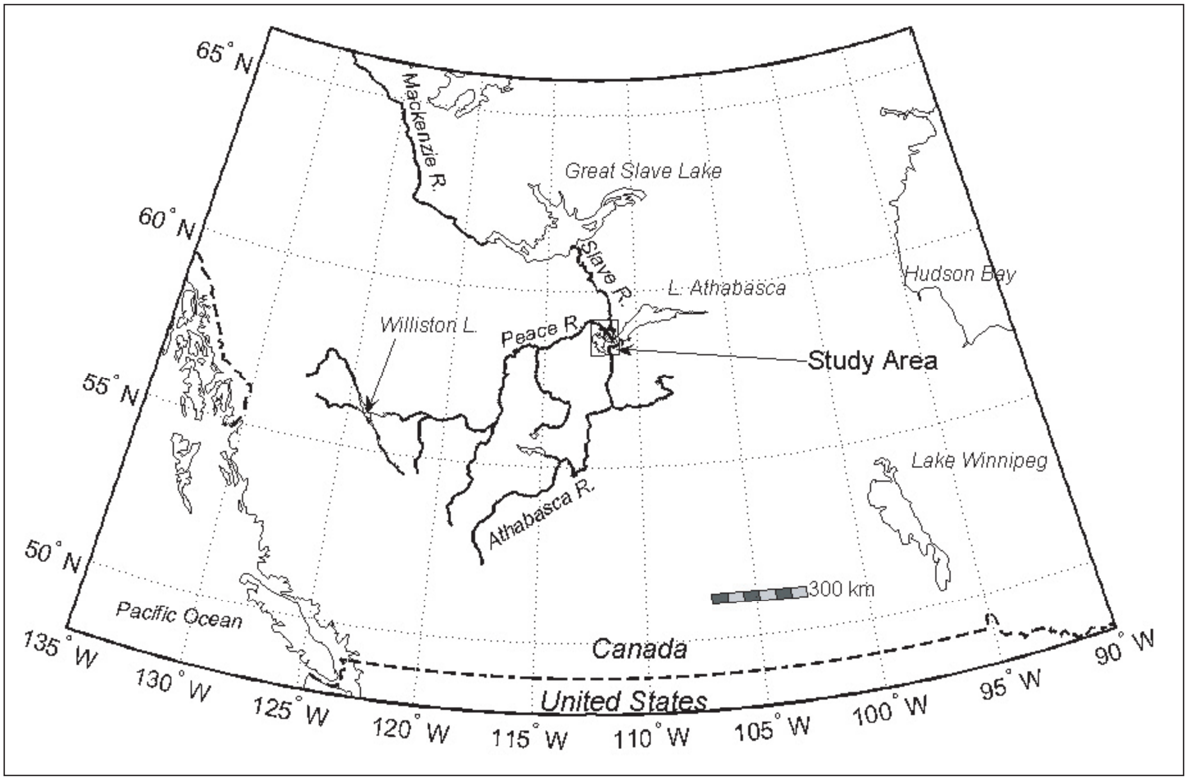

Figure 1. Map showing location of Peace-Athabasca study area and major rivers. For close-up map of study area see Figure 3.

Class-A evaporation pan measurements from nearby locations suggest that mean annual lake evaporation on the PAD exceeds mean annual precipitation (Wolfe *et al.*, 2005).

Data

Hydrologic Data

Daily measurements of total precipitation, snow depth, and average daily temperature for the period 1967 to 1998 at Ft. Chipewyan (58° 46' N, 111° 06' W, 232 m), daily mean streamflow for gauges on the Peace and Athabasca Rivers, and daily water-level measurements for Lake Athabasca at Ft. Chipewyan, Crackingstone Point and Goldfields were obtained from BC Hydro (Jay Joyner, personal communication). The three daily water-level records were merged to create an estimated continuous series, 1934 to 1999, of mean water level at Ft. Chipewyan for the time window July 11 to 20. Details on construction of this series from the daily data are available elsewhere (http://www.ncdc.noaa.gov/paleo/recons.html). The same ten-day seasonal window was used by Stockton and Fritts (1973) in their earlier tree-ring study of the PAD. This seasonal window is later than any expected short-term disruption from spring ice-jam floods and is representative of the mid-summer period when water levels usually reach high levels in response to sustained annual runoff from winter snowmelt in the upper reaches of the main rivers. The July 11 to 20 mean water level in metres above mean sea level is referred to hereafter as "water level".

Observed water level averages 209.54 m and ranges from a low of 208.47 in 1945 to a high of 211.33 m in 1935 (Figure 2). The lowest consecutive three-year sequence occurs in 1968 to 1970. This low occurred during the filling period (1968 to 1972) of W.A.C. Bennett Dam, but also happened to coincide with dry conditions in the watersheds of the Peace and Athabasca Rivers (Bennett, 1970). The water levels plotted in Figure 2 are positively autocorrelated (r_1 = 0.42, $N = 66$, $p < 0.001$, one-tailed test).

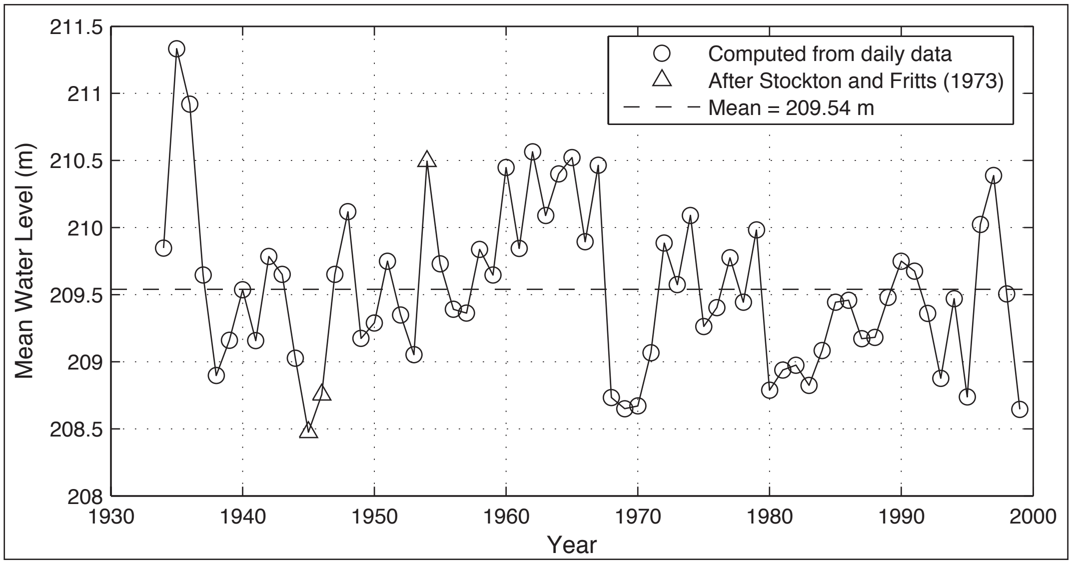

Figure 2. Annual variations in ten-day-mean (July 11 to 20) observed water level of Lake Athabasca at Ft. Chipewyan, 1934-99.

Tree Rings

Increment core tree-ring samples were collected from a total of 106 *P. glauca* trees at eight sites on the PAD between July 31 and August 8, 2001 (Figure 3). If possible, at least two core samples were taken from each tree. Most sampled trees were growing on alluvial formations along the natural levees of river channels or in sloughs or perched basins offset from the channels. Sample site MAW, a bedrock island, was elevated about 30 m above the PAD. Topography at other sites was nearly flat, with sampled trees growing no more than about three metres above the nearby open-water surface of lakes, ponds or rivers.

Several additional sets of tree-ring data or reconstructions are used in this paper. The ring widths from Stockton and Fritts (1973) were downloaded from the International Tree-Ring Data Bank (ITRDB) (http://www.ncdc.noaa.gov/paleo/treering.html). Stockton and Fritts

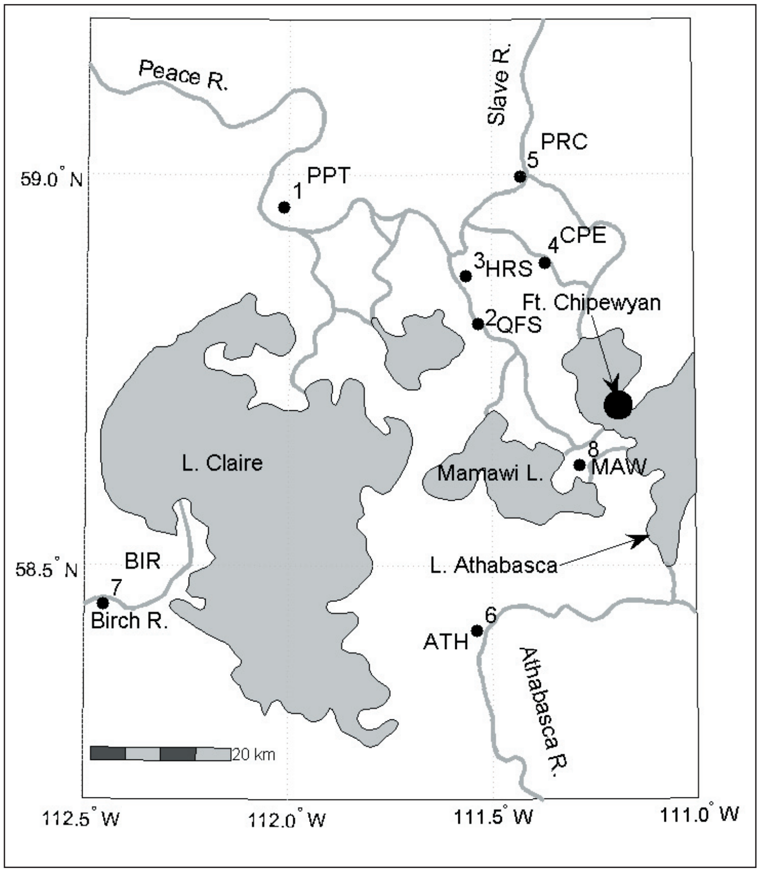

Figure 3. Site map showing locations of eight tree-ring sites collected in July and August, 2001. Sites numbered as in Table 1.

Table 1. Listing of tree-ring sites.

N[1]	Name[2]	Lat	Lon	El (m)	Access
1*	PPT, POINT PROVIDENCE	58.959	112.012	219	Helicopter
2*	QFS, QUATRE FOURCHES	58.797	111.536	216	Boat
3	HRS, HORSESHOE SLOUGH	58.871	111.563	219	Helicopter
4*	CPE, REVILLON COUPE	58.890	111.380	214	Boat
5*	PRC, PEACE/ROCHERS	58.998	111.429	217	Helicopter
6*	ATH, ATHABASCA RIVER	58.417	111.538	219	Helicopter
7	BIR, BIRCH RIVER	58.451	112.454	217	Helicopter
8	MAW, MAMAWI LAKE	58.629	111.285	236	Helicopter

[1] Numbered as in Figure 1; asterisk means site also collected by Stockton and Fritts (1973)

[2] Chronology code and name

(1973) collected at five of the same sites sampled in 2001 (Table 1). A set of 46 standard tree-ring chronologies from western Canada, (48°-66° N, 90°-135° W) covering the period 1866 to 1965, and gridpoint values of reconstructed Palmer Drought Severity Index (PDSI) (Cook *et al.,* 2004) were also downloaded from the ITRDB. A reconstructed time series of the Pacific Decadal Index (MacDonald and Case, 2005) was obtained from Glenn MacDonald (personal communication, 2005).

Methods

Tree-Ring Processing

Tree rings from the 2001 collection were crossdated and measured by standard procedures (Stokes and Smiley, 1968). To remove age-related or size-related trends, measurements were converted to "core indices" by fitting a smooth curve to the ring widths and computing the index as the ratio of the ring width to the fitted curve in each year. The ring widths from Stockton and Fritts (1973) were similarly re-processed to ensure uniformity of the basic tree-ring data. For each site, ring widths were detrended using a spline with 50 percent response wavelength (Cook and Peters, 1981) equal to the median length of ring-width series at the site. This strategy amounts to removal or damping of variations at wavelengths longer than the typical ring-width series at a site.

The core indices were then averaged to compute the site chronology, a mean-value function whose uncertainty decreases as more trees become available. The year at which the sample size (number of trees) becomes adequate to summarize the unknown population tree-ring signal at the site was estimated with the expressed population signal statistic (EPS), a function of the sample size and the mean between-tree correlation of core indices (Wigley *et al.,* 1984).

Alternative summary time series of tree-ring variation on the PAD were constructed by two methods. First, a PAD-mean tree-ring series was defined as a sample-size-weighted mean of chronologies available in any year. For this series, which extends back to the earliest year of tree-ring data at any site, the weights were set proportional to the number of trees at each site, and were constrained to sum to 1.0 in each year. Second, a principal component analysis (Mardia *et al.,* 1979) was run on the standard chronologies, and the time series of scores of the first component (PC#1) was used to describe the primary mode of growth variation. Unlike the PAD-mean series, PC#1 extends no earlier than the first year in common to all eight sites.

Reconstruction Modelling

The time series of PC scores of the tree-ring chronologies were converted to estimates of water level by multiple linear regression (Weisberg, 1985) of water level on scores of principal components (PCs) of standard site chronologies. Standard chronologies rather than residual chronologies were used because the observed water levels are significantly autocorrelated. PC scores for years t and $t+1$ were considered as possible predictors of water level in year t. The lagged PCs were included in the predictor pool to allow the model to adjust for possible excessive autocorrelaton of tree-ring indices over water level or for possible lagged response of growth to water-level variations. Predictors were entered into the equation forward-stepwise such that each new predictor resulted in the maximum possible reduction of residual variance. To reduce the chance of overfitting, the predictor pool was restricted to include only the most important PCs in terms of chronology variance explained (Mardia *et al.,* 1979).

As a further safeguard against overfitting, stepwise validation (e.g., Wilks, 1995; Meko, 1997; Hidalgo *et al.,* 2000) was applied such that entry of predictors was terminated if a predictor resulted in a reduced accuracy of prediction in cross-validation (Michaelsen, 1987). Cross-validation skill was measured by the reduction-of-error statistic, or RE, defined as

$$\mathrm{RE} = 1 - \frac{\mathrm{SSE}_1}{\mathrm{SSE}_2} \qquad (1)$$

where SSE_1 is the sum-of-squares of differences of observed and reconstructed water level for the validation data and SSE_2 is the sum-of-squares of departures of the reconstructed water from the calibration-period mean observed water level (Fritts *et al.,* 1990). An RE < 0 indicates no skill, as a more accurate reconstruction would result from substitution of the observed calibration-period mean water level as the estimate for each year.

Statistical Analysis of Reconstruction

Annual water levels were smoothed with 10-year, 25-year and 50-year Gaussian filters to emphasize low-frequency variations. The filters are defined such that the frequency response of the n-year filter is 0.50 at a wavelength of n years (Mitchell *et al.,* 1966). Sample spectra were estimated by the smoothed periodogram method of spectral analysis (Bloomfield, 2000).

The Mann-Whitney, or rank-sum, test (Conover, 1980) was used to test the null hypothesis that two samples from different parts of a time series are from the same population. This is essentially a test that the samples are from distributions with the same median (Conover, 1980). In applying the test, the observations from the two samples are lumped together, sorted in order of magnitude, and assigned ranks from smallest to largest. The sums of the ranks of observations from each of the two samples is then computed, and a function of the smaller of those rank-sums is the test statistic.

The Pearson correlation coefficient, r, was used to measure the strength of linear relationship between time series. Statistical significance of r was judged by a t-test, as described in Snedecor and Cochrane (1989), after adjustment of sample size for first-order autocorrelation of the individual series as recommended by Dawdy and Matalas (1964). The notation ($r = \ldots, N = n_1(n_2), p = $) is used to describe the significance of correlation, where n_1 and n_2 are the sample size before and after adjustment for autocorrelation, and p is the p-value for a two tailed test of the null hypothesis of zero correlation.

Results

Chronology Development and Time Series Variations in Tree-Ring Index

The maximum sample size, or number of trees, at a site ranges from 11 to 29 (Table 2). The mean between-tree correlation varies little from site-to-site and computations of the expressed population signal (EPS) suggest that five to nine trees are required to adequately approximate the population tree-ring behaviour at a site. The critical sample depth (EPS = 0.85) is reached as early as 1736 at ATH, but not until 1873 at MAW. Sample size typically becomes adequate according to the EPS criterion by the early 1800s. Because water levels were reconstructed from multiple chronologies, reconstruction is probably justified to the early 1800s.

The 50 percent response wavelength of splines used to detrend ring widths ranges from 118 years at MAW to 201 years at ATH (Table 2). The differences in selected splines reflect differences in median length of ring-width series at the sites (see Methods). It is important to recognize that any water-level variation at wavelengths much longer than the 50 percent response wavelengths is removed in the detrending.

The principal components analysis (PCA) indicates the eight chronologies share a strong common tree-ring

Table 2. Summary statistics of Peace-Athabasca Delta tree-ring chronologies.

			Chronology Statistics[2]			
N	Code	Period[1]	Size	r_{bt}	Year$_c$	Fit
1	PPT	1698-2000	22(7)	0.56	1788(5)	152-yr
2	QFS	1712-2000	29(13)	0.51	1771(6)	138-yr
3	HRS	1801-2000	12	0.56	1817(5)	155-yr
4	CPE	1742-2000	27(12)	0.47	1825(7)	127-yr
5	PRC	1687-2000	25(10)	0.55	1803(5)	162-yr
6	ATH	1708-2000	19(11)	0.41	1736(9)	201-yr
7	BIR	1757-2000	14	0.57	1805(5)	129-yr
8	MAW	1801-2000	11	0.46	1873(7)	118-yr

[1] First and last years of measured ring widths at the site

[2] Statistics of the site chronology: Size = maximum number of trees in any year of chronology, with number of trees from Stockton and Fritts (1973) collection in parentheses; r_{bt} = mean between-tree correlation; Year$_c$ = critical year, or year in which the expressed population signal (EPS) reaches 0.85 (corresponding number of trees in that year in parentheses); Fit = wavelength at which the frequency response of the detrending spline for the site is 0.5.

signal (Table 3). The loadings for PC#1, accounting for 63 percent of the chronology variance, are all positive and of comparable size. PC#1 can therefore be considered an alternative to the PAD-mean tree-ring index as a summary time series for tree-ring variations on the PAD. PC#1 is the only PC with an eigenvalue exceeding 1.0, suggesting that PC#1 alone summarizes the important spatial structure in the tree-ring dataset (Mardia *et al.*, 1979). PC#2, with large negative weights on ATH and MAW and positive weights on CPE and PRC, accounts for an additional ten percent of the chronology variance. Sites ATH and MAW are in the southern part of the study area (Figure 3), suggesting that PC#2 might be a tree-growth mode reflecting differential importance of Athabasca and Peace River influences on water level (a south/north contrast). On the other hand, because MAW is the sole bedrock-outcrop site in the collection and ATH is 30 km upstream from Lake Athabasca along the Athabasca River, PC#2 could be a mode of growth variation related to differential importance of local precipitation and river runoff to water level.

The time series of the PAD-mean index and PC#1 describe fluctuations in tree growth averaged over the PAD, or the common tree-ring signal among chronologies (Figure 4, top). The two series, after scaling to remove differences in mean and variance, are nearly identical and are characterized by high-amplitude fluctuations in the 20th century. Growth peaked in the mid-1930s and mid-1960s, and bottomed out in the mid-1940s and early 1980s. Earlier, less severe, periods of extended low growth were centred near 1760 and 1890. Earlier periods of high growth occurred in the 1730s and 1850s. Variations before 1800 are increasingly uncertain because of small sample size and dropping out

Table 3. Principal component loadings on tree-ring chronologies.

Site	PC#1	PC#2	PC#3	PC#4	PC#5	PC#6	PC#7	PC#8
PPT	0.40	0.08	-0.01	0.15	0.41	0.43	0.23	0.64
QFS	0.38	-0.11	-0.11	0.20	0.42	-0.51	-0.60	0.01
HRS	0.39	0.08	0.25	-0.18	-0.10	-0.62	0.59	0.07
CPE	0.34	0.46	0.22	-0.39	-0.45	0.13	-0.46	0.19
PRC	0.39	0.29	0.23	0.16	0.25	0.30	0.11	-0.72
ATH	0.31	-0.46	-0.39	-0.68	0.10	0.17	0.04	-0.18
BIR	0.32	0.13	-0.69	0.41	-0.46	-0.00	0.12	-0.05
MAW	0.28	-0.67	0.43	0.31	-0.39	0.16	-0.08	0.01
%Var[1]	62.71	10.04	7.86	6.35	5.30	3.74	2.61	1.39

[1] Percent of variance explained, analysis period 1801 to 2000.

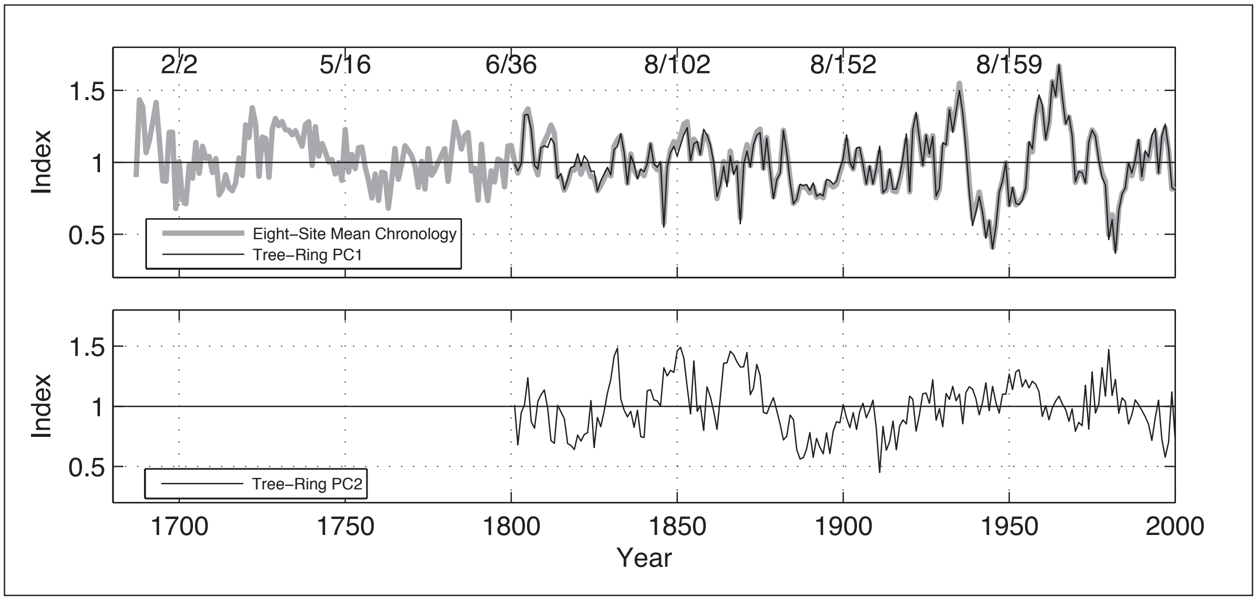

Figure 4. Time series of annual variations in tree-ring index on Peace-Athabasca Delta from eight tree-ring chronologies. Top: eight-site-mean index (PAD-mean) and first principal component of the eight chronologies. Bottom: second principal component of the eight chronologies. Sample size (number of sites/number of trees) annotated at 50-year intervals along top of figure. The PC time series have been scaled and shifted to the same mean and variance as PAD-mean for the 1801 to 2000 overlap period.

of individual chronologies. The series have considerable variability at decadal and longer time scales, but spectral analysis indicated no regular periodicity.

The time series of PC#2 describes fluctuations in a contrast of growth anomalies across the PAD (Figure 4, bottom). PC#2 is characterized by low-frequency variation, with lows centred near 1820 and 1890. The signs of the loadings (Table 3) indicate that lows in PC#2 occur when growth in the central and northern PAD is low relative to growth at MAW and ATH. During the broad low in the PC#2 series near 1890, growth was still below normal at MAW and ATH, but the growth suppression was less severe than at other sites.

Hydrologic Interpretation of Tree-Ring Fluctuations

An exploratory correlation analysis of water level against 54 tree-ring chronologies in Canada (see Data) for the common period 1934 to 1967 confirmed that the water-level signal is relatively strong in the PAD chronologies developed for this study. The PAD chronologies have seven of the eight highest correlations ($0.62 \leq r \leq 0.73$). The other PAD site (BIR), has $r = 0.40$, which ranks tenth highest of the 54 correlations. The two ITRDB chronologies with higher water-level correlation than BIR (CANA130, $r = 0.44$, CANA131, $r = 0.57$) are both *P. glauca* and are located within 140 km of Ft. Chipewyan. Their relatively high correlations probably reflect a common regional climatic signal related to the precipitation or river-runoff input to Lake Athabasca.

The significant correlation of the PAD chronologies with water level must come from covariation of water level and tree growth with some other hydroclimatic variable or set of variables. The climatic conditions associated with high water levels might also be expected to favour high soil moisture in the root zone of the trees and reduced transpiration, and so to favour reduced internal water stress in the trees. High precipitation on the PAD, for example, will increase soil moisture levels at the trees, but will also likely be associated with increased runoff from local watersheds. Flooding due to high levels on the Peace River might not be accompanied by high local precipitation, but will directly affect water levels and could affect soil moisture through inundation of the levees and perched basins on which most of the tree-ring sites are located. Groundwater is another possible pathway of linkage, with rising water levels in the lakes and channels leading to higher water tables and movement of moisture into the root zone. The possible driving hydrologic and climatic factors are numerous and intercorrelated, complicating the task of singling out which are most important to tree-ring variation. Correlations of PAD-mean tree-ring index with seasonal climatic variables aggregated from daily data at Ft. Chipewyan support a positive growth response to cool wet conditions in the growing season. Correlations with total water-year precipitation, maximum snow depth in the first two weeks of April, and summer (June to September) mean temperature are 0.09, 0.15 and -0.19, respectively. The sample size for these correlations is extremely small (21 to 27 observations), and with this small sample size none of the correlations are statistically significant (0.05 significance level), but the direction of correlations is consistent with a drought response.

The importance of hydrologic and climatic fluctuations to tree growth is probably amplified by favourable timing relative to the phenology of the trees. In a previous tree-ring study of *P. glauca* at sites 100 km north of the sites in Figure 3, June precipitation was identified as the most important seasonal climatic factor to ring-width variation (Larsen and MacDonald, 1995). Correlations of monthly precipitation at Ft. Chipewyan with tree-ring PC#1 and PC#2 corroborate a late-spring and early summer precipitation signal in *Picea glauca* (Figure 5). Monthly precipitation correlations are generally positive for PC#1. The most significant months are June concurrent with the year of tree growth and May and June of the preceding year. PC#2 is generally negatively correlated with monthly precipitation over the 16-month period, with most significant correlations in July and February of the current year. Periods of high precipitation locally therefore tend to be associated with low scores on PC#2 (Figure 4, bottom). Low scores on PC#2 in turn are associated with relatively high growth at elevated sites MAW and ATH (Table 3). These PC loadings and sign of regression coefficient are consistent with PC#2 serving to discriminate water level changes strongly driven by local precipitation from changes driven by more remote runoff events.

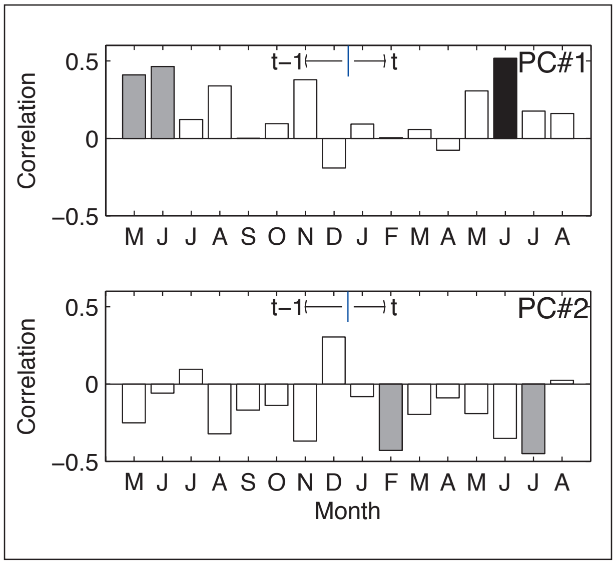

Figure 5. Correlations of monthly precipitation at Ft. Chipewyan, 1967-98, with PC#1 and PC#2 of standard tree-ring chronologies. Top: correlations with PC#1. Bottom: correlations with PC#2. Bars indicate correlations for months May of year preceding growth-year to August of growth-year. Significance of correlation (two-tailed test) indicated by shading (black = 99 percent, gray = 95 percent). Sample size for correlations varies from 24 to 27 because of missing precipitation observations. Significance not adjusted for autocorrelation.

Water-Level Reconstruction

Calibration of water level with PC#1 and PC#2 of tree-ring index for the 65-year period 1935 to 1999 resulted in the following reconstruction model

$$\hat{y}_t = 209.5187 + 0.2604x_{t,1} + 0.1541x_{t+1,2} \qquad (2)$$

where $\hat{y}_t$ is the predicted water level in year t in metres above mean sea level, $x_{t,1}$ is the score of PC#1 of the eight tree-ring chronologies in the same year, and $x_{t+1,2}$ is the score of PC#2 in the following year. Recall that PC#1 has positive weights on all eight chronologies and is therefore a proxy for PAD-wide tree-ring variation (Table 3). This predictor probably reflects an overall positive relationship between moisture availability to the trees and tree growth. As described previously, PC#2 could represent a spatial contrast imparted by differing importance of Athabasca River and Peace River influences, or alternatively a contrast in importance of local precipitation and more remote runoff influences. Entry of PC#2 at a lag of one year may reflect a delay in response due to the inertia in the tree biology or the hydrology (e.g., water levels or precipitation in summer of one year still affecting tree vigor the following year). A lagged response of *P. glauca* growth to precipitation has previously been reported by Larsen and MacDonald (1995).

The model accounts for 36 percent of the variance of water level in the calibration period and is statistically significant ($F = 17.53$, $p < 0.000001$). Positive skill of cross-validation is indicated by the reduction-of-error statistic (RE = 0.29). A residuals analysis did not indicate significant autocorrelation of regression residuals. The reconstructed water levels for the calibration period are more highly autocorrelated than the observed water levels ($r_{1,\text{rec}} = 0.66$, $r_{1,\text{obs}} = 0.42$), but this bias is expected because the regression model assumes the true predictand is the sum of the reconstructed predictand and random (not autocorrelated) noise.

The weak, though statistically significant, water-level signal in the annual reconstruction is enhanced with smoothing (Figure 6). For example, the correlation of observed and actual water levels jumps from 0.60 to 0.84 when series are smoothed with a 10-year Gaussian filter. Decadal and longer fluctuations may therefore be more accurately depicted than might be inferred from the rather modest regression statistics of the annual reconstruction.

Time Series Features of Smoothed Reconstruction

Periods of persistent or recurring low or high water levels can be inferred from smoothed time series plots of the long-term (1801 to 1999) reconstruction (Figure 7). Major lows are centred on 1888, 1944 and 1982. Lesser lows are centred on 1818 and 1917. The dominating high is centred on 1964. Lesser highs are centred on 1850 and 1934. Lows quantified as running means of the reconstruction are listed in Table 4. As might be expected from the smoothed time series plots (Figure 7), the 1940s and 1880s to 1890s dominate the rankings. For 10-year averaging, reconstructed water levels near 1890 were lower than at any other time since 1801.

A comparison of the smoothed reconstructed water levels (Figure 7) with the time series of PAD-mean tree-ring index plotted in Figure 4 (top) indicates that the relative severity of the 1890 low is amplified by the reconstruction model beyond what might be inferred from a simple interpretation of the mean PAD tree-ring index as a water-level proxy. This amplification is imparted by PC#2. The sign of the coefficient on PC#2 is consistent with a gradient toward more severe suppression of tree-growth from south to north across the PAD in the 1880s. The sign is also consistent with accentuated growth suppression at the sites most likely to derive moisture from processes linked with Peace River fluctuations.

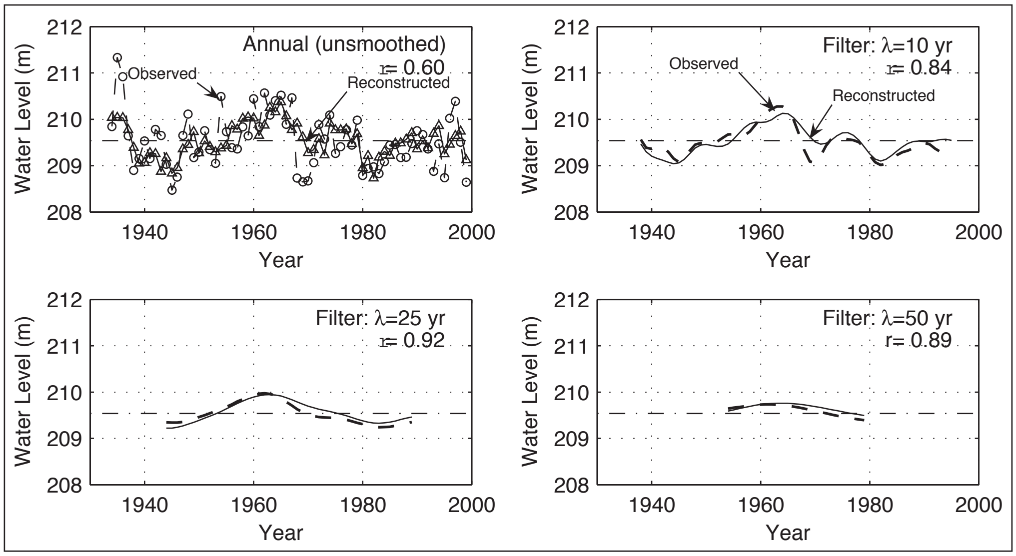

Figure 6. Time series plots illustrating improved agreement of observed with reconstructed water level with smoothing of time series.

Table 4. Lowest running means of water level[1].

Rank	5-year	10-year
Obs	208.47[2] (1945)[3]	209.13 (1989)
1	208.73 (1982)	209.04 (1894)
2	208.83 (1945)	209.06 (1895)
3	208.87 (1943)	209.06 (1893)
4	208.92 (1886)	209.09 (1896)
5	208.93 (1885)	209.12 (1897)
6	208.95 (1980)	209.12 (1892)
7	208.96 (1946)	209.12 (1947)
8	208.99 (1893)	209.13 (1948)
9	209.00 (1890)	209.14 (1898)
10	209.01 (1892)	209.17 (1946)

[1] The lowest observed mean is followed by the ten lowest reconstructed means

[2] Units are m above sea level

[3] Number in parentheses is ending year of running mean

Reconstructed time series of PDSI (Cook *et al.,* 2004) were extracted for selected gridpoints (Figure 8) for a perspective on spatial contrasts in moisture near 1890. These PDSI reconstructions are in a sense "independent" of the water-level reconstruction as none of the same tree-ring chronologies are shared by the reconstruction models. Interpretation of the PDSI series is admittedly speculative, as validation skill is zero for the Cook *et al.* (2004) gridpoints in northwestern Canada (RE statistics from http://www.ncdc.noaa.gov/paleo/treering.html). The selected gridpoints are near A) the Lake Athabasca study area, B) the headwaters of the Athabasca River, and C) the headwaters of the Peace River. The smoothed PDSI series for these gridpoints further support a "drier north" scenario near 1890 (Figure 9, middle): the Peace River headwaters were at the end of the driest reconstruction period on record, while the Athabasca headwaters were near normal moisture. A tree-ring reconstruction of Athabasca River streamflow likewise indicates near normal runoff on the Athabasca River near 1890 (Bonin and Burn, 2005).

Spectral analysis of the annual reconstructed water level of Lake Athabasca, 1801 to 1999, failed to reveal

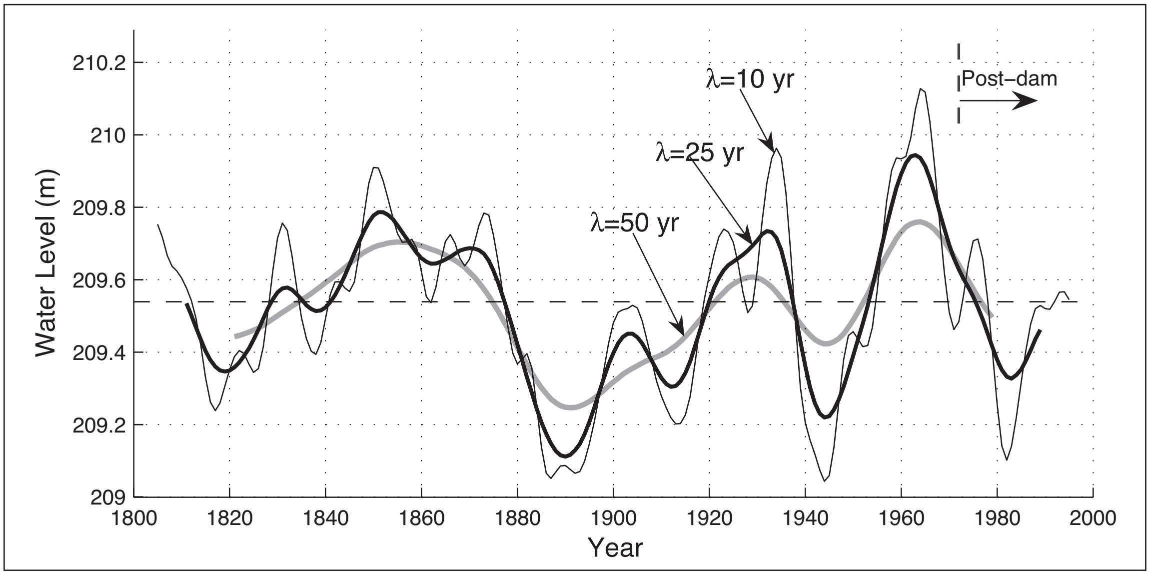

Figure 7. Time series plots of smoothed long-term reconstruction of Lake Athabasca water level. Annotated is the wavelength of the 0.50 frequency response of each Gaussian filter used.

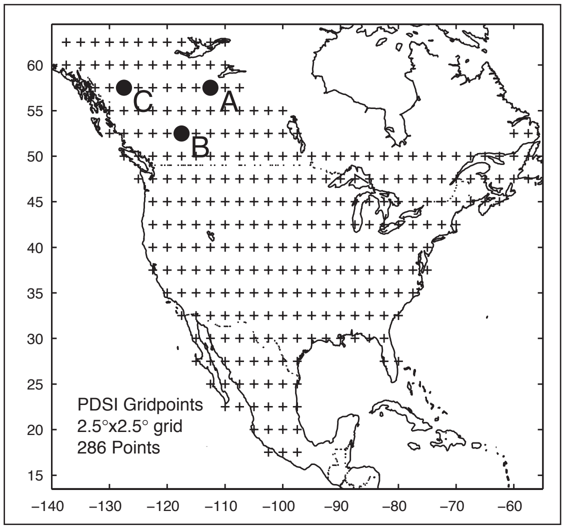

Figure 8. Map showing gridpoints of reconstructed drought index series selected for comparison with reconstructed water level. Point A is centred nearest the Peace-Athabasca Delta tree-ring study area. Point B is in the headwaters region of the Athabasca River. Point C is in the headwaters region of the Peace River. Grid after Cook *et al.* (2004).

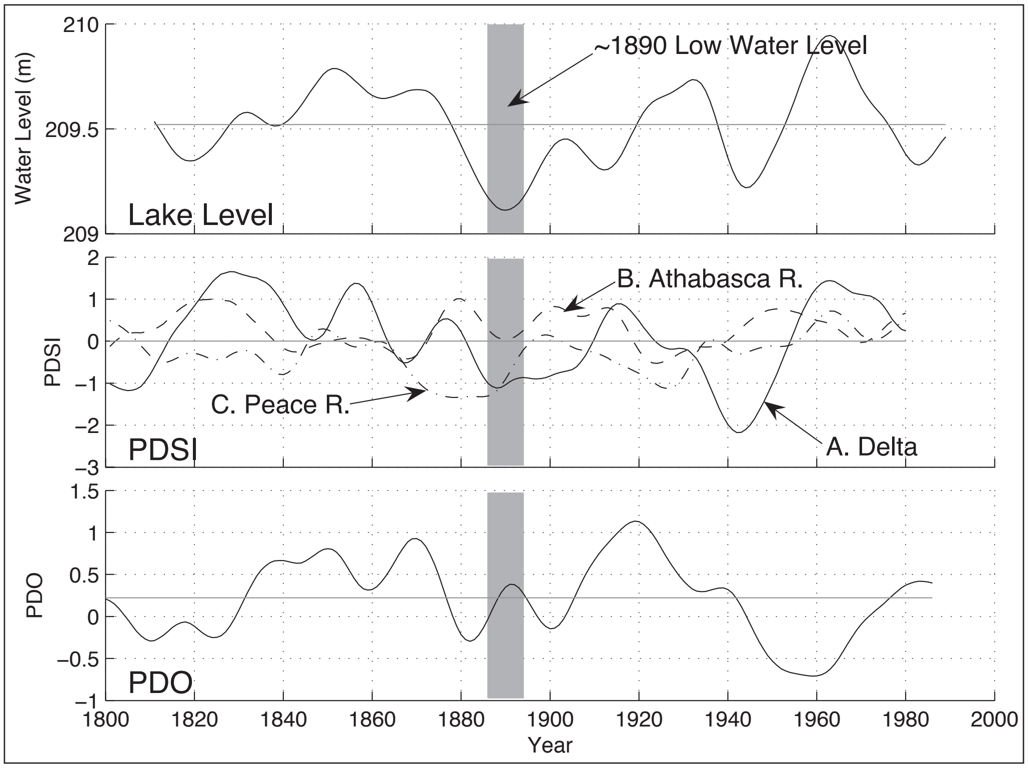

Figure 9. Smoothed time series of hydrologic-related variables reconstructed from tree rings. Top: water level of Lake Athabasca. Middle: gridpoint Palmer Drought Severity index (PDSI) for gridpoints A, B and C shown on map in Figure 8. Bottom: index of Pacific Decadal Oscillation (PDO). All series smoothed with 25-year Gaussian filter. Horizontal lines are the long-term means of reconstructed water level and PDO for available data (before smoothing) in time window 1800-1999, and "normal" or zero PDSI. PDSI from Cook *et al.* (2004) and PDO from MacDonald and Case (2005).

any significant periodicity, but did show that much more of the variance is found at wavelengths longer than ten years (77 percent) than is characteristic of white noise (20 percent). Because low-frequency variations in precipitation and runoff elsewhere in western North America have been linked statistically to eastern North Pacific Ocean temperatures through the Pacific Decadal Oscillation (PDO) (Mantua *et al.,* 1997), a tree-ring-reconstructed PDO (MacDonald and Case, 2005) was examined for timing of PDO swings relative to the 1890 low in reconstructed water levels. The reconstructed PDO at that time was near normal (Figure 9, bottom). Moreover, no consistent phase relationship between reconstructed PDO and water level is evident over the full length of the series.

Pre-Dam and Post-Dam Comparison

The great variability in reconstructed water levels at decadal and longer timescales (Figure 7) implies that many years of data are needed to assess any effect of the dam on water level, and in this respect the relatively short (1972-99) post-dam segment of the observed water level series is still perhaps too short to draw meaningful conclusions. Nevertheless, an assessment was made using the full observed record and extended reconstructed record to place the most recent 28 years in a long-term perspective.

Box-plot summaries of annual water levels before and after construction of the dam show a slight decline in the median in both the observed and reconstructed water levels (Figure 10). For the observed data, changes from pre-dam to post-dam are as follows: lower median (209.65 m to 209.44 m), lower high extremes, and more negative skew in the middle of the distribution (lower part of box stretched out relative to upper part). The reconstructed data show these same qualitative differences from 1935-67 to 1972-99, and a drop in median from 209.53 m to 209.48 m.

Results of the Wilcoxon rank-sum test (see Methods) applied to pairs of samples to test the null hypothesis that the samples before and after filling of the dam come from the same distribution are listed in Table 5. The results for the observed data support (but marginally) an alternative hypothesis that the water level samples pre-dam and post-dam come from different distributions. The results for the reconstructed levels for the same sub-periods do not show a significant change. The results for the reconstruction using the longer pre-dam period also do not show a significant decline. The *p*-value for the comparisons on reconstructed level becomes less significant with the extended pre-dam period (1801-1967), suggesting

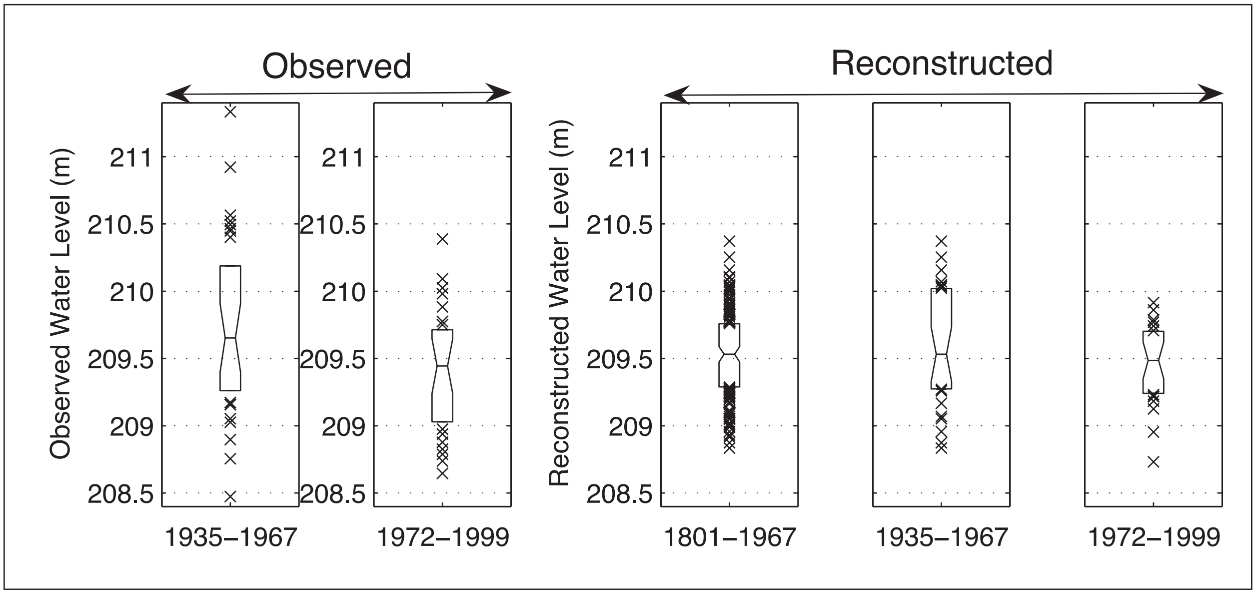

Figure 10. Box plots illustrating differences in Lake Athabasca water level before and after construction of W.A.C. Bennett Dam.

Table 5. Results of Wilcoxon rank-sum test that samples of water level before and after filling of dam come from distributions with equal medians.

	Sample 1		Sample 2			
Data Type	Period	Median[1]	Period	Median	Rank Sum	p[2]
Observed	1935-1967	(209.65)	1972-1999	(209.44)	727	0.04*
Recon.	1935-1967	(209.53)	1972-1999	(209.48)	785	0.23
Recon.	1801-1967	(209.53)	1972-1999	(209.48)	2541	0.46

[1] median water levels (m)

[2] *p*-value, probability of rank sum as low as observed if samples from same population

that were longer records available the test on observed water levels might not reach the 0.05 significance threshold.

The long-term reconstruction, extending back to A.D. 1801, gives a total of 140 overlapping 28-year segments of reconstructed water level for comparison with the 28 years since the construction of the dam. The empirical cumulative distribution functions (cdf's) of the 140 sample means, standard deviations, ranges, and first-order autocorrelation coefficients are plotted in Figure 11. In the same figure, the probability point of the 1972-99 (post-dam) segment is marked and the corresponding probability points and values of the statistics are annotated. For example, the 1972-99 standard deviation (lower left plot) is 0.286 m, which is larger than 64 percent of the sample standard deviations from the 140 reconstruction segments. In terms of non-exceedance probability, if a 28-year sub-sample were picked at random from the 140 samples in the long-term record, the probability of not exceeding the 1972-99 standard deviation is 0.64.

The remaining cdf's in Figure 11 can similarly be evaluated to place other post-dam water-level statistics in a long-term context. In summary, the following is indicated about the post-dam, 1972-99, segment:

1. The mean is relatively low in a long-term context;
2. The standard deviation is relatively high;
3. The range is relatively high; and
4. The first order autocorrelation is relatively low.

None of the computed statistics for 1972-99 is so unusual as to be an outlier in the sense of having an empirical non-exceedance probability lower than 0.05 or greater than 0.95. These results show a lack of statistical evidence for an effect of the dam on the annual time series of water levels. Caveats are that the percentage of lake-level variance accounted for by the tree-ring model is small and the post-dam sample size is small.

Consistency of Reconstruction

A comprehensive history of Fort Chipewyan (Wuetherick, 1972) contains a few entries relevant to anomalies of water level from "normal". Perhaps the strongest is a quote from a Father Petitot in 1882: "… the extraordinary decrease for many years in the waters of the rivers and lakes, which has destroyed fish-life to an immense extent and driven away wild fowl, having caused such a famine that many died of hunger and misery between 1879 and 1881…" This historical note is consistent with the reconstruction, as reconstructed water level drops sharply for several years beginning in 1879. A plot of three-year running means (not shown) reaches its lowest level since 1818 in the period 1879-81.

Consistency of reconstructed water levels with gridpoint PDSI reconstructions of Cook *et al.* (2004) has already been discussed. Water levels correlate weakly ($r = 0.20$, $N = 190(85)$, $p = 0.06$) with reconstructed PDSI for the gridpoint nearest the PAD over the period 1801 to 1990. A strong correlation is not expected given that the reconstructions are of different hydrologic variables and the Cook *et al.* (2004)

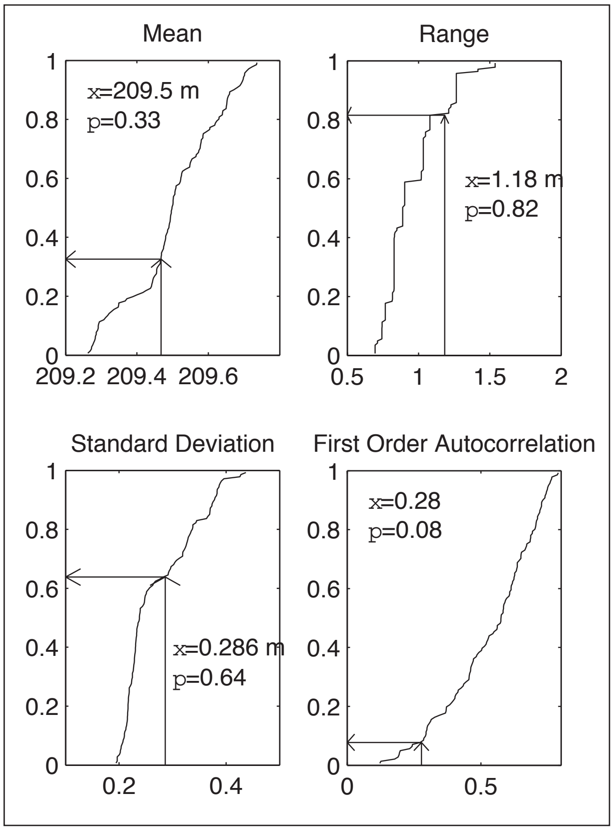

Figure 11. Empirical cdf's of statistics of reconstructed flow for all possible 28-year sub-periods. Arrows and annotation refer to the sample statistics for post-dam period, 1972-99.

reconstructions are highly uncertain for gridpoints near the PAD.

The ten-year Gaussian smoothed version of reconstructed water levels (Figure 7) was compared with 20-year moving average reconstructed flows of the Saskatchewan River, whose watershed is some 600 km to the south (Case and MacDonald, 2003). The major low in water level near 1890 does coincide with low streamflow on the Saskatchewan. The major low in Saskachewan flow near 1840, on the other hand, occurs at a time of generally high reconstructed water levels on the PAD.

The 20th century low-frequency variations in reconstructed water level depicted in Figure 7 are remarkably synchronous with tree-ring variations reported by Larsen and MacDonald (1995) for *P. glauca* tree-ring chronologies 20 to 115 km north of site #1 in Figure 3. The chronologies in Larsen and MacDonald, (1995) are on upland sites, presumably unaffected by Peace River flooding or lake level changes, and exhibit significant climate correlation primarily with June precipitation (at Ft. Smith). The chronologies do not show a major growth suppression coincident with the low in smoothed water levels near 1890 (Figure 7).

Major differences were found between the new reconstruction and the reconstruction of the same water-level variable generated by Stockton and Fritts (1973). Their reconstruction, referred to here as SF73, covers the period 1810 to 1967. Their regression model accounts for 80 percent of the variance of water level (1935-67 calibration period) compared with 36 percent for the new reconstruction (1935-99 calibration period). The new reconstruction correlates significantly with SF73 in 1935-67 ($r = 0.71, N = 33(11), p = 0.013$), but not at all in earlier years ($r = -0.10, N = 125(63), p = 0.43$). As the patterns of tree-ring variation are similar in chronologies from SF73 and the newly developed chronologies, the lack of correlation must come from the statistical models converting tree rings to estimates of water level. A short calibration period can contribute to high uncertainty in reconstructions (Brockway and Bradley, 1995), and the calibration period for SF73 was limited to the available 33 years of overlapping tree-ring and water-level data. A short calibration period combined with a complicated reconstruction model risks model overfitting. The SF73 reconstruction employed a canonical regression model with 12 predictors selected by automated rules from a much larger pool of potential predictors. Model validation, a safeguard against overfitting, and now routine in dendroclimatology (Fritts *et al.*, 1990), was not applied in SF73—primarily because the calibration set was so short. (Cross-validation approaches for reconstruction models had not yet been developed.)

In an attempt to replicate the modelling results of SF73, a model was tried with all eight tree-ring PCs, lags 0, +1 (16 variables) in the predictor pool, 12 predictors chosen by forward stepwise regression, and a calibration period 1935-67. This model was found to account for more than 75 percent of the calibration period variance of observed water level, but had a negative RE statistic, indicating no skill of validation.

Conclusions

Tree-ring results presented here support earlier findings of a statistically significant positive relationship between white spruce (*P. glauca*) tree growth and water levels on the Peace Athabasca Delta. The new data considerably revise the existing tree-ring reconstructed water-level information and extend the record back to A.D. 1801. The increased sample depth of tree-ring chronologies improves the ability of the samples to capture the population tree-ring signal on the PAD and to provide reliable estimates of hydroclimatic variations. A simple two-predictor regression model relating water level (July 11 to 20 mean) of Lake Athabasca to PCs of tree-ring index accounts for 36 percent of the variance of water level. The model indicates that decadal-average water levels near 1890 were lower than at any time since the start of the currently reliable tree-ring record in A.D. 1801. Comparison of the reconstruction with other tree-ring information for Canada suggests the water-level low near 1890 was associated primarily with low flows of the Peace River, with near normal runoff from the Athabasca River and possibly mildly dry local conditions on the PAD.

Time series plots and statistical analysis of the reconstruction show large variability of water level on timescales of decades and longer, with no clear link to the Pacific Decadal Oscillation and no identifiable change associated with the construction of W.A.C. Bennett Dam on the Peace River. It is acknowledged that the strength of water-level signal in the current network of tree-ring collections is weak and that uncertainty remains in distinguishing the water-level signal from local precipitation and other correlated hydrologic and climatic variables. A network of drought-sensitive tree-ring chronologies in the Canadian Rockies, especially in the watershed of the Peace River, would provide better information on river flows affecting the water balance of the PAD. Additional tree-ring collections on the PAD, with emphasis on deepening the sample size in the early part of the record, would likely improve the water-level information. A sampling strategy of well-replicated subsets of chronologies at upland sites (e.g., bedrock island), lowland sites (e.g., along levees of channels) and perched basins, is suggested to help discriminate water-level changes driven by local climate variations from those driven by variations in flow regimes of major rivers.

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