Tree-Ring Reconstructions of Streamflow in the Churchill River Basin, Northern Saskatchewan

Antoine L. Beriault and David J. Sauchyn

Abstract: This study describes the development of 13 moisture-sensitive tree-ring chronologies from the Churchill River Basin of northern Saskatchewan, and their application to estimate streamflow prior to the initiation of direct monitoring in 1929. Most of these new tree-ring records extend back to the early or mid-19th century, with their length limited by the lifespan of trees growing in fire-dominated boreal forest environments. Ring-width index chronologies are significantly correlated with mean annual and summer streamflow across the watershed; those records that were highly (above 0.6) correlated with streamflow were chosen as potential predictors in linear regression models. Robust models (accounting for between 40 and 53 percent of total variance) were developed for three gauges in the basin and used to estimate annual streamflow at these locations since ca. AD 1840. Periods of above average annual flow include 1853 to 1882, 1894 to 1904, 1932 to 1936 and 1946 to 1979. Annual flows were consistently below average during 1840 to 1852, 1883 to 1893, 1905 to 1921, 1937 to 1945 and 1980 to 1997. Some of the most severe and sustained low flows have occurred in recent decades. Although these proxy hydrological records are relatively short compared to many other tree-ring estimates of past streamflow, they provide an expanded context for evaluating the variability recorded by stream gauges and the conventional reference hydrology for water supply planning and management in northern Saskatchewan.

Résumé : La présente étude décrit l'évolution de treize séries dendrométriques sensibles à l'humidité provenant du bassin de la rivière Churchill dans le nord de la Saskatchewan et leur application pour estimer l'écoulement fluvial avant le début de la surveillance directe en 1929. La plupart des nouvelles séries dendrométriques remontent au début ou à la moitié du XIX^e siècle, leur durée étant limitée par la durée de vie des arbres poussant dans des forêts boréales qui sont souvent la proie d'incendies. Les chronologies de largeurs des anneaux sont corrélées de façon significative avec le débit annuel moyen et le débit d'été à la grandeur du bassin; les relevés qui étaient hautement corrélés avec les débits (au-dessus de 0,6) ont été choisis en tant que prédicteurs éventuels dans des modèles de régression linéaire. Des modèles robustes (représentant entre 40 et 53 pour cent de la variance totale) ont été conçus pour trois jauges dans le bassin et utilisés pour estimer le débit annuel à ces endroits depuis environ 1840.

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Les périodes de débit annuel supérieur à la moyenne englobent de 1853 à 1882, de 1894 à 1904, de 1932 à 1936 et de 1946 à 1979. Les débits annuels étaient inférieurs à la moyenne, de manière constante, de 1840 à 1852, de 1883 à 1893, de 1905 à 1921, de 1937 à 1945 et de 1980 à 1997. Certains des débits les plus bas et les plus soutenus se sont produits au cours des décennies récentes. Bien que ces relevés hydrologiques indirects soient relativement courts comparativement à de nombreuses autres estimations d'anneaux de croissance pour les débits passés, ils offrent un contexte plus vaste pour l'évaluation de la variabilité enregistrée par les jauges de rivières et par la traditionnelle hydrologie de référence, et ce, à des fins de planification et de gestion de l'approvisionnement en eau dans le nord de la Saskatchewan.

Introduction

An understanding of the long-term variability of stream discharge is a key component of the scientific basis for sustainable water management. However, the relatively short length of instrumental records limits the understanding of the historical variability of water supplies. In Canada, stream gauge records seldom exceed 100 years and most are considerably shorter, especially in remote areas. These data are unlikely to capture the full range of hydroclimatic variability, especially in terms of the frequency of prolonged wet and dry intervals lasting for years.

The study of tree rings in relation to hydroclimate enables the reconstruction of climatic and hydrologic histories that pre-date instrumental data (Stahle, 1996). Annual variations in tree-ring width reflect daily and seasonal growth limiting processes. Where soil moisture is limiting, standardized tree-ring widths tend to correlate with hydroclimatic variables such as precipitation and stream discharge (Loaiciga *et al.*, 1993). Reconstructions of stream discharge are possible because tree growth, like stream discharge, captures and integrates a regional moisture signal (Meko and Graybill, 1995). Climatic conditions that result in reduced runoff (i.e., low precipitation and high evapotranspiration) are expressed in trees as low water potential and suppressed growth (Kozlowski, 1971).

The objective of this study was to reconstruct historical stream discharge in the Churchill River Basin of northern Saskatchewan (Figure 1) using tree rings. This basin represents a large gap in the current North American tree-ring network (International Tree-Ring Databank, 2006), primarily due to its remote location but also because maximum tree age in the southern boreal forest is generally limited to 200 to 300 years by extensive forest fires. The Churchill Basin is also a key component of the hydrological system used to generate hydroelectricity downstream in Manitoba and provides 19 percent of Manitoba Hydro's total energy supply (Girling, 2006). Planning for hydroelectric power production aims to support firm energy demand (forecast peak load demand plus minimum of 12 percent reserve capacity) under hydrological conditions equivalent to the lowest observed river flow in the Churchill-Nelson system (Girling, 2006: 8). During the drought of record for the entire system (1939 to 1940), average annual flow in the Churchill River was extremely low (less than 400 m^3/s; Figure 2). In the Churchill Basin, this event was part of an eight-year interval (1937 to 1944) of persistently low average annual discharge.

Relatively few studies have used tree-ring data to reconstruct past streamflow in Canada. Case and MacDonald (2003) modelled streamflow in the Saskatchewan River Basin using four tree-ring chronologies. Watson and Luckman (2005) produced an approximately 300-year summer streamflow record for the Bow River in Banff National Park by combining tree-ring reconstructions of the winter mass balance of Peyto Glacier with a reconstruction of April to August precipitation for Banff. The present study extends the application of dendrohydrology into northern Saskatchewan and estimates flow conditions during the 19th and 20th centuries using a network of 13 tree-ring chronologies from the Churchill River Basin.

The Churchill River Basin

The Churchill River Basin (Figure 1) begins in east-central Alberta, drains a large part of Saskatchewan (from north of Reindeer Lake to south of La Ronge) before passing into Manitoba and emptying into Hudson Bay. With short, cool summers and cold winters, streamflow is dominated by snowmelt

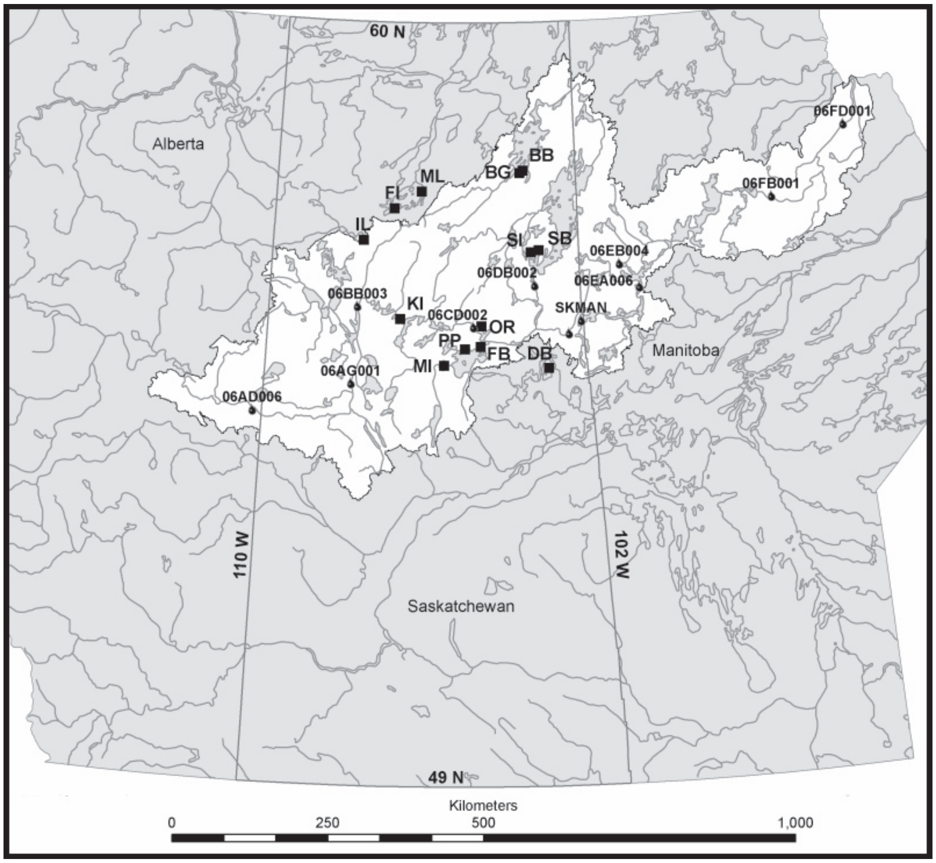

Figure 1. The Churchill River Basin and the tree-ring sampling sites (squares) and stream gauges (water drops).

runoff and, to a lesser extent, summer convective precipitation. The western portion of the basin is part of the Interior Plains and vegetation is primarily the mixed coniferous and deciduous forest of the Mid-Boreal Uplands (Wiken, 1986). Further east, and for most of its course, the river flows over the Precambrian Shield, which is irregularly interrupted by thin lacustrine and fluvioglacial deposits. The Shield influences the basin's hydrologic regime, as infiltration is confined to fractures, evapotranspiration is low and lakes are common. At its termination, the river enters the Hudson Bay lowland, an extensive wetland region comprised of fens, peat mounds and plateaus, with open stands of spruce up to the subarctic treeline. Snowmelt dominates the early season runoff regime, with late summer rainfall accounting for peak flows in some sub-basins (Wiken, 1986).

The two most important control structures on the Churchill River are the hydroelectric generating station at Island Falls, Saskatchewan, built in 1929 near the provincial boundary, and the artificial channel at the north end of Southern Indian Lake, Manitoba, that redirects 60 percent of the streamflow to the Nelson River for hydroelectric power generation.

Tree-Ring and Streamflow Data

Prior to this study, the International Tree Ring Data Bank (2006) contained tree-ring records from two sites in the Churchill River Basin of northern Saskatchewan. These prior collections did not target trees growing in likely moisture-stressed environments and instead were developed to support studies of boreal forest dynamics (BOREAS, 2006) or studies of continental or hemispheric-scale climate change (Schweingruber *et al.*, 1993). Therefore, new collections of tree-ring samples were made at 13 sites (Figure 1) during the summer of 2002 and 2003, both to expand the existing, sparse network of tree-

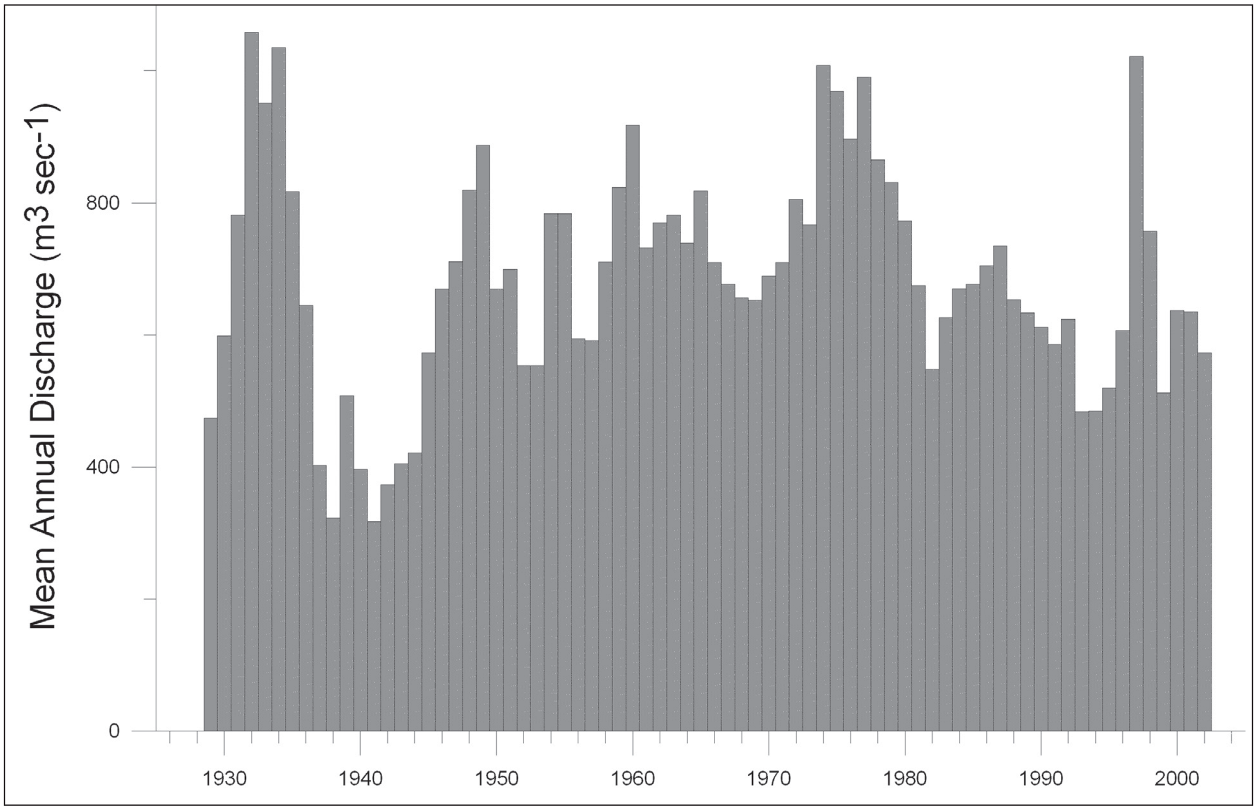

Figure 2. The longest instrumental record for the Churchill River: mean annual flow (m^3 sec^{-1}) at Sandy Bay (gauge 06EA002, Figure 1) from 1929 to 2002. This gauge is upstream of the hydroelectric generating stations on the Churchill River. The seasonal distribution of flow is regulated, however, by control structures to maintain the levels of lakes upstream.

ring sites in the basin and to collect samples from moisture-limiting environments.

Sampling locations were chosen based on two primary factors: exposure to forest fire and the growth environment. In the boreal forest of northern Saskatchewan, the interval between stand replacement fires is about 130 years (M. Johnson, Saskatchewan Research Council, personal communication, 2002), and old living trees and sub-fossil wood are restricted to a very small proportion of the area.

In an attempt to maximize tree age, sampling concentrated on locations that were close to large water bodies (which are likely to act as fire breaks) and avoided areas of known recent fires. Trees growing in environments where water supplies are limited are more likely to be sensitive recorders of moisture availability and drought, and so sampling focused on sites with characteristics including bedrock outcrops with thin soil cover, rapidly drained soil (e.g., glaciofluvial deposits), moderate to steep slopes, high local relief, and a southern aspect. Because these types of sites are common on the Canadian Shield, sampling was concentrated in the central part of the basin.

Sampling was initially restricted to *Picea glauca* (white spruce) to eliminate potential species-specific differences in growth response to local climate conditions (Stockton, 1975). However, due to the limited extent of white spruce within the basin, *Pinus banksiana* (jack pine) and *Picea mariana* (black spruce) were also sampled. At each site, cores were extracted from two opposing radii near the base of at least 20 living trees using a 5.1 mm Haglof increment borer (Grissino-Mayer, 2003). These samples were supplemented by cross-sections cut from deadfall.

Streamflow data were obtained from Environment Canada's HYDAT 2000–2.01 database (Water Survey of Canada, 2006) and the Prairie Provinces Water Board (PPWB, 2006), which maintains a record of natural flow for the Churchill River at the Saskatchewan/Manitoba border (SKMAN). Records were chosen for analysis if the gauge was established prior to 1980, had less than 20 percent missing values and recorded runoff from at least five percent of the basin. Of the 76 hydrometric stations reported for the Churchill River Basin, ten met these criteria (Figure 1). Gauge data were rehabilitated using the mean-ratio approach, where missing observations are replaced by values equivalent to those measured at a nearby gauge with similar discharge.

Table 1 gives summary statistics and the results of normality testing for the stream discharge data. Mean annual flow ranges from 19.15 m^3 sec^{-1} for gauge 06AD006 (the Beaver River at Cold Lake Reserve, Alberta) to 861.0 m^3 sec^{-1} for gauge 06EB004 (the Churchill River above Leaf Rapids, Manitoba). The coefficient of variation has two ranges: 20 to 39 percent and 61 to 84 percent. The five gauges in the latter category record high interannual variability. The gauge records are autocorrelated, some extremely so, reflecting the persistence of flow levels from year to year, most likely as a function of lake and wetland storage. Partial autocorrelation coefficients at lags greater than one year were not statistically significant.

Tree-Ring Index Chronologies

Tree cores were processed in the University of Regina Tree-Ring Lab following standard procedures (Cook and Kairiukstis, 1990). Initial dating based on visual comparisons of growth patterns among trees at each site were verified using the program COFECHA (Grissino-Mayer, 2001). A common signal was enhanced by removing series that had low correlation

Table 1. Streamflow records: gauges and statistics.

Gauge	Station name	Span	Drainage area (km^2)	N/R[1]	Mean Q (m^3 s^{-1})	CV[2]	Lilliefors Test[3]	AC_1[4]
06AD006	Beaver River at Cold Lake Reserve	1955-2005	14500	N	19.15	0.77	X	0.377
06AG001	Beaver River below Waterhen River	1971-1997	45000	N	48.02	0.68	X	0.587
06BB003	Churchill River near Patuanak	1930-1995	78700	N	118.42	0.61	X	0.670
06CD002	Churchill River above Otter Rapids	1963-2005	119000	N	264.91	0.39		0.616
06DB002	Reindeer River at Outlet of Reindeer Lake	1929-1987	62600	R	320.24	0.23		0.437
06EA002	Churchill River at Sandy Bay	1929-2005	212000	R	684.70	0.25		0.715
06EA006	Churchill River above Granville Falls	1946-2005	230000	R	772.89	0.20		0.629
06EB004	Churchill River above Leaf Rapids	1973-2005	244000	R	861.00	0.20		0.669
06FB001	Churchill River below Fidler Lake	1960-2005	271000	R	504.02	0.84	X	0.899
06FD001	Churchill River above Red Head Rapids	1971-2005	287000	R	484.56	0.72	X	0.797
SKMAN	Churchill River at SK/MB Boundary	1977-2001	215000	N	676.14	0.20		0.390

[1] Regulated (R) or Natural (N) flow

[2] Coefficient of Variation: standard deviation as a fraction of the mean

[3] X: H_o rejected, where H_o is the null hypothesis of no departure from a normal distribution

[4] First-order partial autocorrelation coefficient

with the site chronology and truncating or removing series with growth trend anomalies. The program ARSTAN was used to remove age- or size-related trends and compute dimensionless ring-width indices. Individual tree-ring series were detrended using either a modified negative exponential curve or a 100-year cubic spline with a 50 percent variance cutoff. These detrending options are conservative and were chosen in an attempt to preserve low-frequency variability related to climate. For each site, detrended time series were combined to produce three versions of a summary series or 'chronology': the standard chronology (STD) produced by simple averaging, the prewhitened residual chronology (RES) produced by autoregressive modelling and the ARSTAN chronology (ARS), which incorporates some of the original autocorrelative structure of the data (Cook *et al.*, 1990).

Table 2 provides statistics for the 13 ring-width chronologies. The longest record begins in 1766, but only seven of the 13 chronologies exceed 150 years. Mean sensitivities range between 0.200 and 0.349, indicating relatively high interannual variability that often reflects a strong climatic control of growth (Stockton, 1990). Effective chronology signal (R_{eff}) is an estimate of the common variability (signal strength) among the tree-ring series from a single site (Briffa and Jones, 1990). A chronology comprised totally of signal would have a R_{eff} of 1. The values in Table 1 (0.306 to 0.610) indicate chronologies with a reasonably strong common signal. Expressed population signal (EPS) is a measure of the statistical quality of the tree-ring chronology. It varies from .882 to .981 in Table 1, with all chronologies above the 0.850 threshold considered desirable for dendroclimatic data (Briffa and Jones, 1990). The number of series (N) required to achieve the EPS threshold determines the range of years over which the chronology signal can be reliably recovered.

A Lilliefors non-parametric test of normality indicated that 36 of the 39 index chronologies (STD, RES and ARS at 13 sites) are normally distributed. The exceptions are the STD chronologies at Fraser Bay (FB) and Kinapik Island (KI) and the ARS chronology at McGugan Island (MI). First-order autocorrelation (AC) coefficients are reported in Table 2 for the ARS chronologies. The only significant ($p < 0.05$) partial autocorrelation coefficients were of second-order and for just two chronologies (BG and SB). The STD and ARS chronologies have a similar degree of autocorrelation. With the ARS chronology, however, the AC is modelled using a pooled tree-ring data set. Thus, whereas the STD chronology inherits the AC from the original ring-width data, the pooled autoregressive properties of the ARS chronologies are more likely to represent a common signal as a function of the climatic forcing of tree growth. The STD index chronologies were excluded from further analysis given that in theory more of the serial AC reflects growth persistence independent of climate variability than for the ARS chronologies.

Streamflow Reconstruction

The number of significant ($p < 0.05$) correlations between hydrometric records (monthly, calendar and water year discharge in preceding and current years) and the RES (Figures 3) and ARS (Figure 4) index chronologies indicate that the tree-ring data are most frequently correlated with mean summer, calendar and water year discharge for the current year. Significant negative correlations, mostly in the colder months, are few (two percent) and are believed to be spurious. The water year is defined to begin in October of the preceding year and end in September of the current year.

There is significant ($p < 0.05$) positive correlation between annual streamflow and tree-ring data across the Churchill River Basin (Table 3). Data from all 11 streamflow gauges correlate with tree-ring records from at least four sites. The white spruce record from Bolen Lake (BG) is significantly correlated with all gauge records, and ring width from two sites (OR and KI) is correlated with all the gauge records but one (06DB002). On the other hand, there are no significant ($p < 0.05$) correlations between streamflow and the tree-ring data from sites DB and ML or with the RES index chronologies from sites FB, SB, SI, IL and PP. The ARS chronologies are more highly correlated with stream discharge than the RES chronologies. Streamflow-tree growth pairs that were highly correlated ($r > 0.6$) were used to guide the selection of predictors (tree-ring chronologies) and predictands (stream gauges) for multiple linear regression models.

Step-wise multiple linear regression was used to model streamflow as a function of: (1) the ARS index chronologies; and (2) the RES index chronologies with lagged predictors to simulate the serial autocorrelation in the streamflow data. Cross-validation was used to assess the predictive skill of the reconstruction equation

Table 2. Standard Index Chronologies: Sites and Statistics.

ID	Name	Sp[1]	N_1[2]	Span	ms[3]	R_{eff}[4]	EPS[5]	N_2[6]	AC_1[7]
BB	Bolen Lake	Piba	26	1817-2002	0.227	0.393	0.926	12	0.659
BG	Bolen Lake	Pcgl	27	1852-2002	0.242	0.541	0.959	6	0.524
DB	Doupe Bay	Pcgl	55	1839-2001	0.218	0.522	0.966	8	0.438
		Pcgl							
FB	Fraser Bay	Pcma	48	1854-2001	0.222	0.460	0.953	9	0.516
FI	Fleming Island	Piba	30	1766-2002	0.226	0.310	0.891	19	0.595
IL	Ithingo Lake	Piba	20	1875-2002	0.222	0.327	0.882	15	0.881
KI	Kinapik Island	Pcgl	79	1840-2001	0.248	0.610	0.981	5	0.433
MI	McGugan Island	Piba	29	1832-2002	0.222	0.336	0.891	15	0.689
ML	MacIntyre Lake	Piba	24	1854-2002	0.209	0.306	0.882	17	0.659
OR	Otter Rapids	Pcgl	33	1879-2001	0.223	0.518	0.966	7	0.686
		Pcgl							
PP	Patterson Peninsula	Pcma	47	1827-2001	0.276	0.536	0.947	8	0.408
SB	Stockhouse Bay	Pcma	33	1835-2001	0.188	0.310	0.919	17	0.466
SI	Sanford Island	Piba	30	1878-2002	0.349	0.480	0.954	8	0.426

[1] Piba: *Pinus banksiana* Pcgl: *Picea glauca;* Pcma: *Picea mariana*

[2] number of tree-ring series (radii)

[3] mean sensitivity - a measure of the high-frequency variation

[4] effective chronology signal - an estimate of the common variability

[5] expressed population signal

[6] number of series required to achieve an EPS ≥ 0.850

[7] first-order partial autocorrelation coefficients (ARS chronologies)

for models that passed the tests of linearity and uncorrelated residuals. Observations were iteratively deleted from the calibration data (full gauge record) and the model was used to predict the deleted observation. Table 4 gives validation statistics for three linear models that did not violate the major assumptions of linear regression and had high predictive skill. The regression models account for between 40 and 53 percent of the total variance in annual flow. The Reduction of Error (RE) statistic is used to determine if streamflow predicted from the regression model is closer to the observations than the mean of the calibration period. Positive values indicate that the model has some predictive skill. The root mean squared error for the validation ($RMSE_v$) measures the average size of the prediction error. $RMSE_v$ is comparable to the standard error of the estimate (SE_e) for the calibration period. The difference between the two validation statistics, and their comparative calibration statistics, is a measure of how well each model verifies.

The regression models were used to predict annual streamflow prior to direct monitoring. The curves in Figure 5 change from solid to dashed when more than 15 percent of the tree-ring signal is lost due to diminishing sample depth. Error bars, approximating the bounds of the 95 percent confidence interval, are also plotted based on $RMSE_v$.

Discussion and Conclusions

The three streamflow reconstructions in Figure 5 describe variability in streamflow across the Churchill River Basin in Saskatchewan, from the headwaters (the Beaver River below Waterhen River) to a gauge on the upper reaches of the main stem (the Churchill River at Patuanak), to the end of the watershed in Saskatchewan (the Churchill River at the SK-MB Border). Within the calibration period, the reconstructed flows track multi-year trends but tend to underestimate high

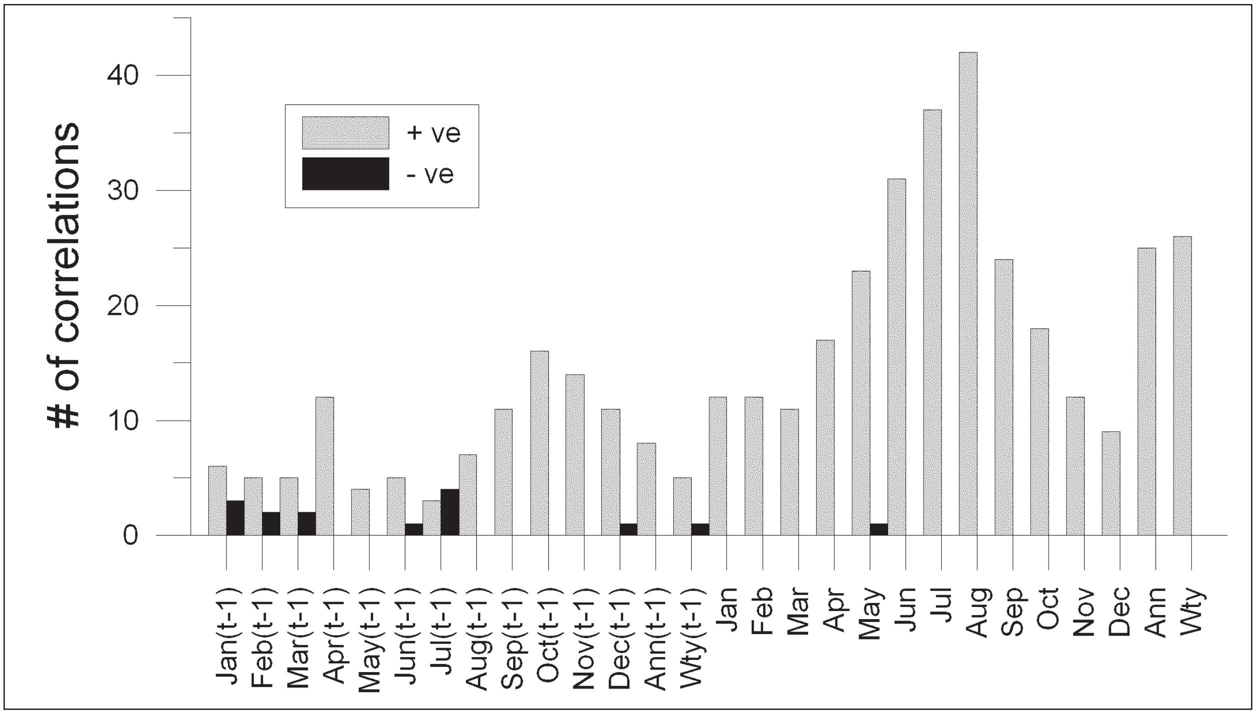

Figure 3. Number of significant ($p < 0.05$) positive (+ve) and negative (-ve) correlations among the hydrometric variables and the residual index chronologies.

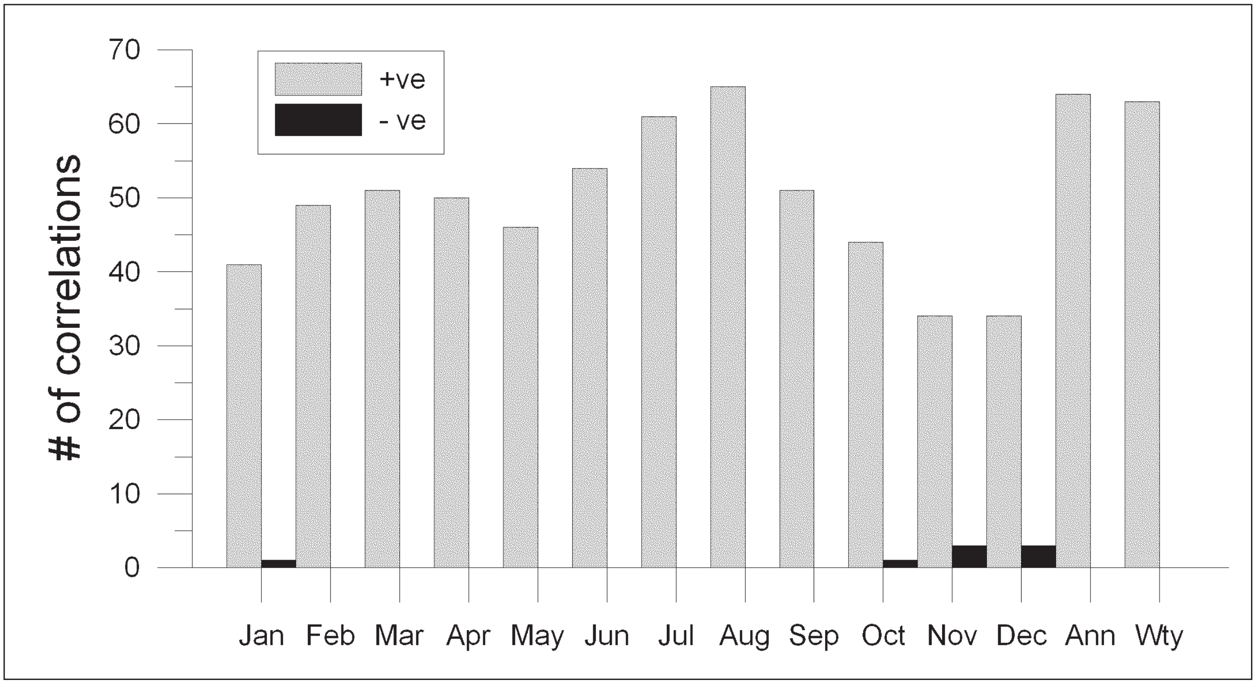

Figure 4. Number of significant ($p < 0.05$) positive (+ve) and negative (-ve) correlations among the hydrometric variables and the ARSTAN index chronologies.

flows, such as during the 1970s in the Beaver River and the late 1990s at the SKMANA gauge. Periods of above average mean annual flow shared by the three reconstructions include 1853 to 1882, 1894 to 1904, 1932 to 1936 and 1946 to 1979. Annual flows were consistently below average in three proxy records during 1840 to 1852, 1883 to 1893, 1905 to 1921, 1937 to 1945 and 1980 to 1997. The last half of the 20th century was characterized by extended periods of above (1946 to 1979) and below (1980 to 1997) average discharge, which are more persistent than those in the earlier part of the reconstructions.

The beginning of the Beaver River reconstruction hints at dry conditions in the upper Churchill River in 1840 to 1852, but the other reconstructions at the downstream gauges are not long enough to characterize flow during this interval over the entire watershed. Furthermore, the Beaver River reconstruction has EPS values below 0.85 during this period, although we argue that it is useful to relax this restriction because of the relatively short lifespan of trees in this region. Dry conditions in the mid-19th century are recorded throughout the western interior of southern Canada and the United States (e.g., Cook *et al.*, 1999; Sauchyn *et al.*, 2003; Woodhouse, 2001). Dendrohydrologic records include low flows during 1841 to 1873 for the South Saskatchewan River (Case and MacDonald, 2003), low mean water levels for Lake Athabasca from 1841 to1860 (Stockton and Fritts, 1973), and drought in the southern Cordillera during 1839 to 1859 (Watson and Luckman, 2004). Thus there is some agreement between the dendrohydrology of the Churchill River Basin and other river basins of the western interior. There is an important difference however. Most previous studies in Saskatchewan have shown that the worst droughts in tree-ring records precede the 20th century and the

Table 3. Significant ($p < 0.05$) correlations of annual stream discharge (A: calendar year, W: water year) with the tree-ring index chronologies (RES: residual, ARS: ARSTAN). Correlations > 0.600 are highlighted in bold.

Tree-Ring Sites:		**BB**		**BG**		**FB**	**FI**		**KI**	
Gauge	**A/W**	**RES**	**ARS**	**RES**	**ARS**	**ARS**	**RES**	**ARS**	**RES**	**ARS**
06AD006	A				0.331				0.418	0.410
06AD006	W				0.371				0.437	0.434
06AG001	A				0.394				0.549	**0.690**
06AG001	W								0.519	**0.662**
06BB003	A				0.504				0.443	**0.656**
06BB003	W				0.547				0.414	**0.664**
06CD002	A		0.315		0.493				0.570	**0.663**
06CD002	W		0.333	0.321	0.511				0.554	**0.693**
06DB002	A		0.352		0.392	0.367				
06DB002	W		0.316		0.349	0.322				
06EA002	A	0.272	0.348	0.371	0.567	0.322		0.235	0.462	0.545
06EA002	W		0.341	0.308	0.540	0.288		0.240	0.409	0.537
06EA006	A	0.336	0.373	0.355	0.579				0.354	0.428
06EA006	W	0.315	0.421	0.317	0.573					0.377
06EB004	A		0.491		**0.653**		0.394			0.502
06EB004	W	0.384	0.511		**0.613**		0.439	0.423		0.379
06FB001	A	0.367	0.565	0.451	**0.721**	0.405			0.319	0.454
06FB001	W	0.408	**0.603**	0.488	**0.747**	0.465				0.451
06FD001	A		0.507	0.434	**0.731**	0.448				0.428
06FD001	W	0.378	0.543	0.407	**0.723**	0.467				
SKMAN	A		0.405	0.474	**0.655**		0.496	0.450	0.473	0.490
SKMAN	W				0.418		0.534	0.476	0.432	0.496

Table 3. continued.

Tree-Ring Sites:		IL	MI		OR		PP	SB	SI
Gauge	A/W	ARS	RES	ARS	RES	ARS	ARS	ARS	ARS
06AD006	A	0.397				0.367			
06AD006	W	0.407				0.361			
06AG001	A					0.521			
06AG001	W					0.492			
06BB003	A	0.517				0.594			
06BB003	W	0.560				**0.630**			
06CD002	A				0.362	0.567	0.361		
06CD002	W				0.366	0.596	0.415		
06DB002	A							0.325	0.325
06DB002	W							0.307	0.307
06EA002	A		0.335	0.319		0.273		0.317	0.317
06EA002	W		0.276	0.333		0.259		0.330	0.330
06EA006	A	0.339				0.300			
06EA006	W	0.329					0.326		
06EB004	A	0.558				0.563	0.449		
06EB004	W	0.560				0.463	0.478	0.389	0.389
06FB001	A	**0.637**			0.452	**0.671**	0.485		
06FB001	W	**0.668**			0.451	**0.699**	0.575		
06FD001	A	**0.629**			0.368	**0.706**	0.438		
06FD001	W	**0.617**				**0.668**	0.455	0.387	0.387
SKMAN	A					0.529	0.431		
SKMAN	W						0.407		

Table 4. Regression model validation statistics.

Station	A/W	Predictors	N[1]	RE	R^2_{adj}	$RMSE_v$ [2]	SE_e [2]
06AG001	A	KI_ARS	27	0.34	0.455	26.07	24.17
06BB003	W	KI_ARS, IL_ARS	66	0.33	0.526	57.48	49.54
06SKMAN	A	BG_ARS	25	0.36	0.404	105.36	103.95

[1] number of observations (years) in the calibration interval

[2] in m^3 sec^{-1}, the units of the predictand, mean annual discharge

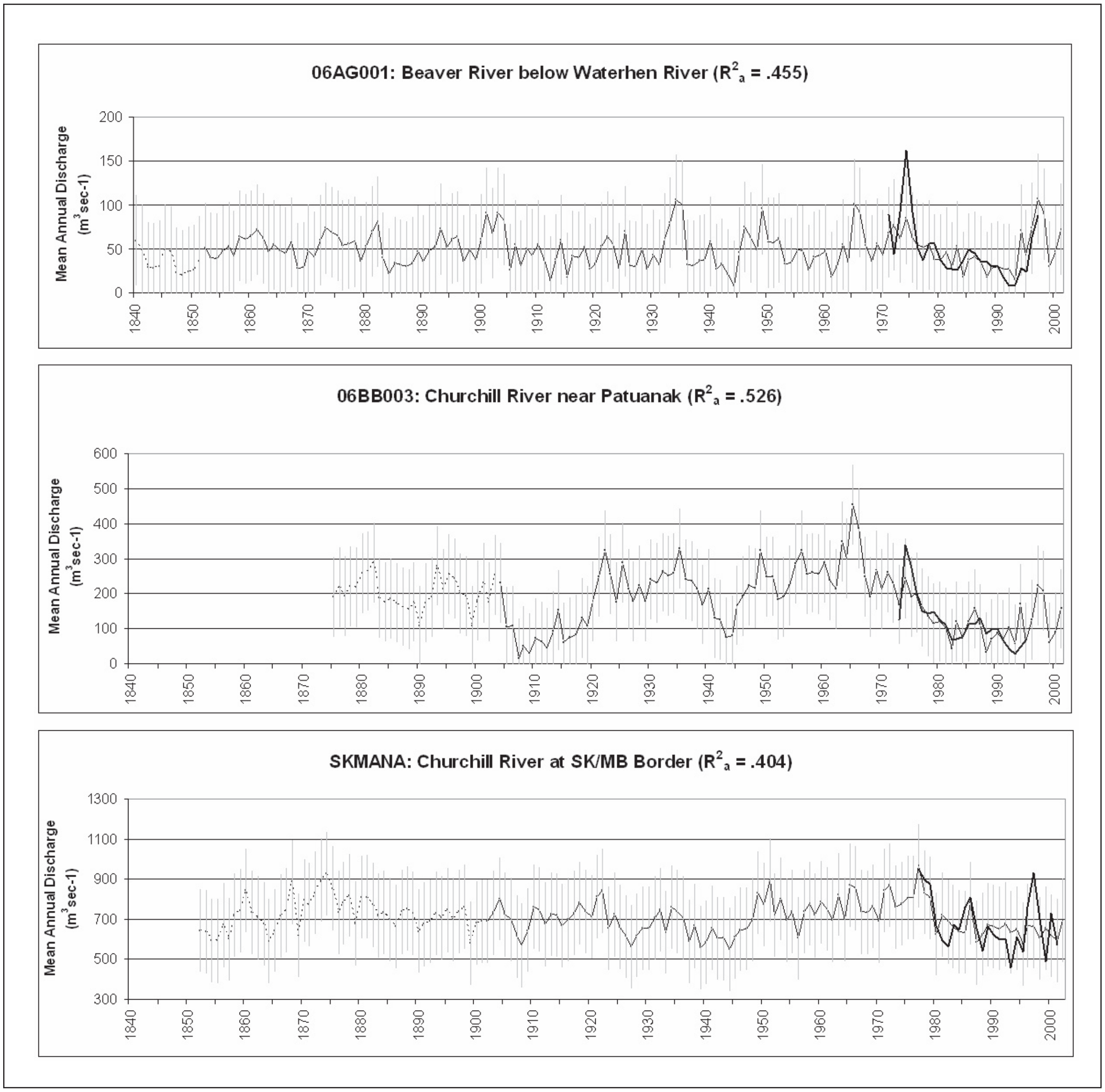

Figure 5. Reconstructions of mean annual discharge from the three validated models. The heavy curve is the gauge record. The section of the proxy record shown with dashed line has an expressed population signal below the critical threshold of 0.850. Vertical lines show the root mean square error. R^2_a is the explained variance adjusted for the number of predictors.

instrumental observation of water and climate (Sauchyn *et al.*, 2003; Case and Macdonald, 2003).

This study produced the first network of moisture-sensitive chronologies for northern Saskatchewan and the first proxy streamflow data for the Churchill River. The length of the reconstructions was constrained by the relatively young age of living trees in the boreal forest. Although the proxy records in this paper are relatively short by tree-ring standards, they indicate that some of the most severe and sustained low flows have been in recent decades. The tree-ring reconstructions provide a context for evaluating the hydroclimatic variability recorded by stream gauges and the conventional reference hydrology for water supply planning and management.

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