TREE RING RECONSTRUCTIONS OF STREAMFLOW FOR THREE CANADIAN PRAIRIE RIVERS[1]

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ABSTRACT: Information regarding long term hydrological variability is critical for the effective management of surface water resources. In the Canadian Prairie region, growing dependence on major river systems for irrigation and other consumptive uses has resulted in an increasing vulnerability to hydrological drought and growing interprovincial tension. This study presents the first dendrochronological records of streamflow for Canadian Prairie rivers. We present 1,113-year, 522-year, and 325-year reconstructions of total water year (October to September) streamflow for the North Saskatchewan, South Saskatchewan, and Saskatchewan Rivers, respectively. The reconstructions indicate relatively high flows during the 20th Century and provide evidence of past prolonged droughts. Low flows during the 1840s correspond with aridity that extended over much of the western United States. Similarly, an exceptional period of prolonged low flow conditions, approximately 900 A.D. to 1300 A.D., is coincident with evidence of sustained drought across central and western North America. The 16th Century megadrought of the western United States and Mexico, however, does not appear to have had a major impact on the Canadian rivers. The dendrohydrological records illustrate the risks involved if future water policy and infrastructure development in the Canadian Prairies are based solely on records of streamflow variability over the historical record.
(KEY TERMS: drought; paleohydrology; dendrochronology; tree rings; streamflow; climate change; Saskatchewan River system; Canadian Prairies.)

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INTRODUCTION

The Saskatchewan River subbasin (SRSB) encompasses the semiarid to subhumid Prairie regions of the provinces of Alberta and Saskatchewan in central Canada. Almost all prairie agricultural enterprise and more than 92 percent of the population of the two provinces occupy this area (Nicholaichuk, 1990). The approximately 364,000 km^2 subbasin includes lands drained by the Bow, Oldman, Red Deer, South Saskatchewan, North Saskatchewan, and Saskatchewan Rivers (Figure 1). Annual precipitation across the subbasin ranges from approximately 1,500 mm at the headwaters in the Rocky Mountains to less than 300 mm in the southern Prairies and is highly variable interannually (Longley, 1953; SNBB, 1972). Due to low and variable rainfall, there is high dependence on streamflow for consumptive and nonconsumptive water uses (McKay *et al.*, 1989). Crop irrigation is the primary water consumer; the irrigation of more than 650,000 ha of agricultural land accounts for over 75 percent of consumptive water use in the region (Bjonback, 1990). Rivers of the SRSB supply water for agricultural, industrial, and municipal needs and are also important for hydroelectric power generation, recreation, and tourism (Lawford, 1992).

A growing dependence on surface water resources in the Prairie Provinces has resulted in an increasing vulnerability to hydrological drought. Over 75 percent of the streamflow of the SRSB originates as snowmelt on the eastern slopes and foothills of the Rocky Mountains. Therefore, the origins of these droughts are removed both geographically and temporally from the regions of greatest impact. As a result, hydrological droughts are often not anticipated (Maybank *et al.*, 1995). For example, during the winter of 1987 to 1988, low snowfall on the eastern slopes (70 to 80 percent of normal) resulted in below average spring runoff and low streamflow on the South

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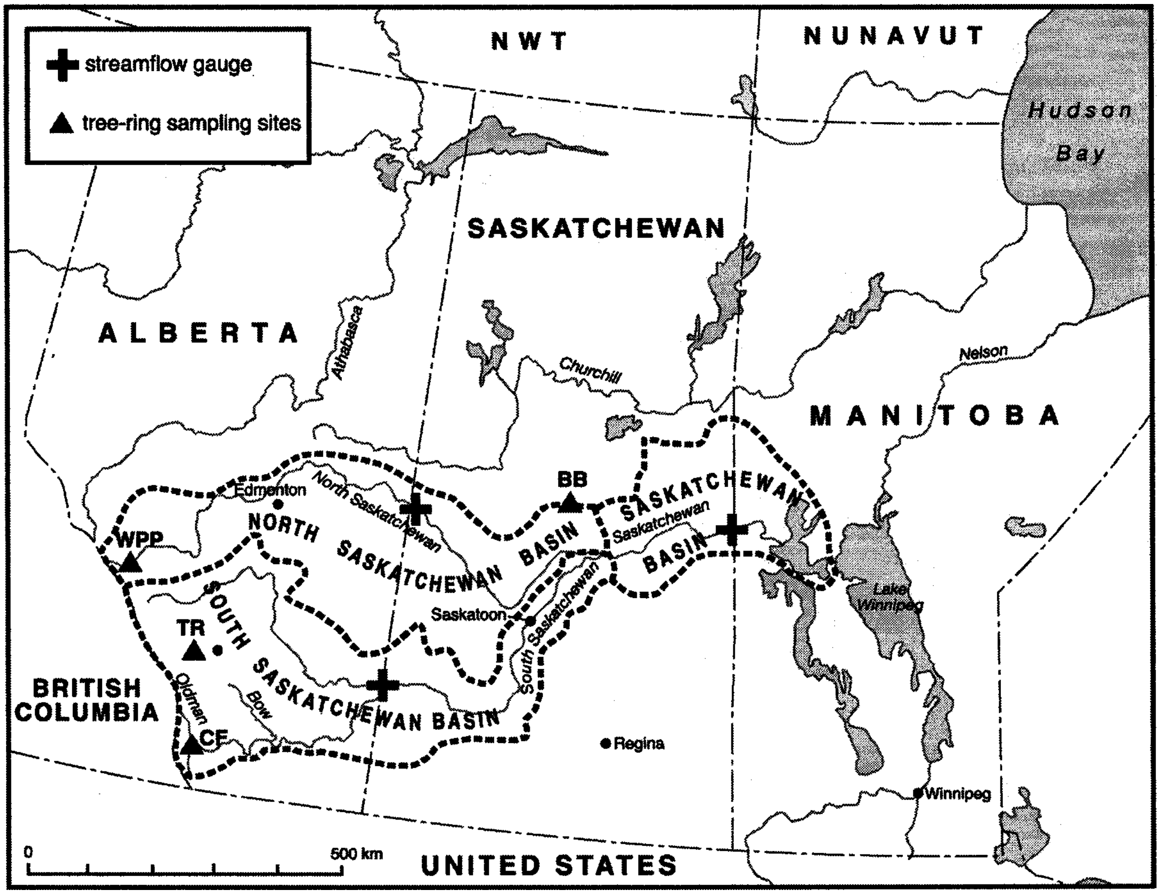

Figure 1. Map Showing the Locations of Tree Ring Sampling Sites (triangles) and Streamflow Gauges (plus marks). Also shown are the drainage areas of the North and South Saskatchewan and Saskatchewan River

Saskatchewan (approximately 33 percent below normal) and Saskatchewan (19 percent below normal at The Pas, Manitoba) Rivers (PFRA, 1988; Lawford, 1992). Because low streamflow had not been anticipated, normal drawdowns of reservoirs had occurred in the summer and fall of 1987, and major water shortages were experienced through the 1988 summer (Lawford, 1992). The 1988 hydrological drought led to low agricultural production due to reduced irrigation, soil erosion, water quality problems, and monetary losses on the order of $73 million in Manitoba as a result of reduced hydroelectricity sales (McKay *et al.*, 1989; Wheaton *et al.*, 1992). More recently, extremely dry conditions in 2001 and 2002 prompted the government of Alberta in April 2002 to propose a new water strategy that would reduce the volume of water flowing into Saskatchewan. As widely reported in the media, this controversial water strategy produced strong protest from the province of Saskatchewan.

Over time, water demand and vulnerability to hydrological drought will likely increase in the Prairie Provinces due to population growth and the increasing intensification of agriculture (Kulshreshtha and Tewari, 1991; Maybank *et al.*, 1995). Drought problems may be further aggravated by the regional impacts of CO_2-induced climate change (Lewis, 1989; Hurd *et al.*, 1999; Ojima *et al.*, 1999). General Circulation Models (GCMs) predict that with a doubling of current CO_2 levels, the Canadian Prairie region could experience rising summer temperatures in the order of 9°C and substantial reductions in soil moisture (Manabe and Wetherald, 1987). As a result of higher evapotranspiration, significant increases in crop and irrigation water demand are anticipated (Cohen, 1991). The predicted impacts of global warming on streamflow are inconsistent. Some GCM scenarios agree that net precipitation in the Rocky Mountains will increase (Cohen, 1991). However, higher temperatures may reduce total snowfall relative to rain and cause earlier spring snowmelt, resulting in reduced snowpack and net streamflow during the growing season (Nkemdirim and Purves, 1994; Yulianti and Burn, 1998; McCabe and Wolock, 1999). Nkemdirim and Purves (1994) predict streamflow decreases of 15 percent in the SRSB with every 1°C increase in temperature. Alternatively, Byrne *et al.* (1999) argue that net streamflow on the Prairies will increase with climate warming due to an increased frequency of synoptic patterns associated with wet winter conditions. The benefits of increased flow, however, would likely be offset by a temporal water supply problem: if earlier snowmelt occurs, peak flow will no longer coincide with peak irrigation demand in June (Byrne and McNaughton, 1991). With economic development of the Prairies reaching the limit of current water supplies, adaptability to either reduced net flow and/or earlier snowmelt will be a major challenge for the region.

There is a clear need for long term records of streamflow in order to understand the natural variability of the SRSB system and to effectively plan future water policy and infrastructure development. Instrumental hydrological data do not provide a long enough record to satisfy this need (Woodhouse and Overpeck, 1998; MacDonald and Case, 2000). However, tree ring data from carefully selected sampling sites can provide an excellent proxy for past streamflow (e.g., Meko *et al.*, 1995). Because the water balances of rivers and moisture stressed trees are largely determined by precipitation and evapotranspiration integrated over days to months, annual growth and streamflow are sensitive to the same climatic signals (Meko *et al.*, 1991, 1995). Tree ring chronologies have been used to reconstruct long term records of streamflow at various locations in the western United States, including the Upper Colorado River (e.g., Stockton and Jacoby, 1976; Hidalgo-Leon *et al.*, 2000), the Colorado Front Ranges (Woodhouse, 2001), the Salt and Verde Rivers (e.g., Smith and Stockton, 1981; Young, 1994), the Upper Gila River (Meko and Graybill, 1995), and the Sacramento River (Meko *et al.*, 2001). In Canada, the use of dendrochronology for reconstructing streamflow and hydrological drought on the Prairies has been suggested (Henoch and Parker, 1972). However, no quantitative reconstructions of streamflow are available. If possible to construct, such long term records would be of use to water resource planning on the Canadian Prairies and an important addition to paleodrought data sets being developed for the North American plains region in general (Woodhouse and Overpeck, 1998).

This study presents the first long term reconstructions of streamflow from tree ring data for the Canadian Prairie region. We present 1,113-year, 522-year, and 325-year reconstructions of total water year (October to September, hereafter "annual") natural streamflow for the North Saskatchewan, South Saskatchewan, and Saskatchewan Rivers, respectively. These long records allow for an investigation of natural streamflow variability within the subbasin over multiple centuries and a comparison of the hydrological history of the basin with other regions of North America where similar proxy climate records are available.

NATURAL STREAMFLOW AND TREE RING DATA

Natural streamflow data were acquired from the Prairie Provinces Water Board (PPWB). The PPWB defines natural streamflow as "the quantity of water which would flow in any watercourse had flow not been affected by human interference." Human interference includes water loss due to reservoir storage and evaporation, consumptive use (predominantly irrigation), and diversions (PPWB, 1976a). As the PPWB is concerned with interprovincial water allocation, natural streamflow is calculated at points closest to interprovincial boundaries. For this study, three boundary point stations were selected for long term dendrohydrological streamflow modeling (see Figure 1): (1) the North Saskatchewan River Deer Creek gauging station (ID 05EF001), 32 km east of the Alberta-Saskatchewan border; (2) the South Saskatchewan River gauging station below the confluence with the Red Deer River (ID 05AK001), 16 km west of the Alberta-Saskatchewan border; and (3) the Saskatchewan River Manitoba Boundary gauging station, 3.2 km west of the Saskatchewan-Manitoba border (ID 05KH008). All natural streamflow records are 86 years in length (1912 to 1998). Details of natural streamflow calculations for the North and South Saskatchewan and Saskatchewan Rivers can be found in PPWB publications (PPWB, 1974, 1975, 1976a, 1976b).

The tree ring chronologies used in this study were obtained from four different sampling sites. Location information and basic chronology statistics for the four ring width chronologies are given in Table 1. Sampling, measuring, and chronology construction were conducted using standard techniques (Stokes and Smiley, 1968; Fritts, 1976; Cook and Kairiukstis, 1990). The maximum number of individual trees incorporated into each chronology ranges from 30 to 51 (in most cases, two cores were taken from each tree sampled). Three sites in Alberta – Towers Ridge (TR), Crowsnest Pass (CP), and Lundbreck Falls (LF) – were sampled in 1992 and used by Case and MacDonald (1995) to develop an approximately 500-year reconstruction of precipitation for the western Prairies. In the present study, samples from CP and LF were combined to develop a single chronology, Crowsnest Falls (CF), to improve sample replication in the early part of the chronology. The TR and CF chronologies are 594 and 522 years in length, respectively (see Case and MacDonald, 1995, for full site

TABLE 1. Tree Ring Sampling Site Information.

Site	Location (˚N, ˚W)	Elevation (m asl)	Species	Chronology Interval*	Length of Chronology (years A.D.)	Chronology Maximum Sample Depth (no. trees)
CF	49°35´, 114˚13´	1,240	*Pinus flexilis*	1470 to 1992	522	50
TR	51°10´, 114˚40´	1,330	*Pinus flexilis*	1398 to 1992	594	47
WPP	52°00´, 116˚27´	1,373	*Pinus flexilis*	883 to 1996	1,113	51
BB	53˚56´, 106˚20´	611	*Picea mariana*	1671 to 1996	325	30

*The interval over which there is a minimum chronology sample depth of three trees.

and chronology development details). Trees at Whirlpool Point (WPP) in Alberta in the Rocky Mountain montane valley of the North Saskatchewan River were sampled in 1996. All Alberta chronologies were developed from *Pinus flexilis* (limber pine) growing in open grown stands on semiarid sites with rapidly drained soils. The 325-year Boundary Bog (BB) chronology was developed from 30 *Picea mariana* (black spruce) trees growing at a site located in Prince Albert National Park, Saskatchewan. The *P. mariana* site was sampled in 1996 [see R. A. Case, 2000, unpublished Ph.D. Dissertation, "Dendrochronological Investigations of Precipitation and Streamflow for the Canadian Prairies," Department of Geography, University of California, Los Angeles, California; and Case and MacDonald (2003), for full site and chronology development details].

In the development of all chronologies, individual ring width series were detrended to remove low frequency variation associated with aging of the tree (Cook *et al.*, 1990). Detrending was accomplished using ARSTAN software (Holmes, 1992) and involved fitting a negative exponential curve or straight line with a negative slope to each individual ring width series. More flexible functions (e.g., splines) were not used in detrending, as growth suppression and release events related to gap dynamics were not seen in the ring width series, likely due to the open grown character of the stands. By dividing the actual value by the curve value for each year, standardized, dimensionless, ring width index series were then derived for each radius. The robust mean of all standardized series yields a "Standard" site chronology for each site. The "ARSTAN" chronology is then derived by adding the autoregressive persistence common to all ring width series to a "Residual" (prewhitened) chronology. In growth climate analyses and model estimation discussed in this paper, the ARSTAN versions of the chronologies were used (Holmes, 1992).

METHODS

The Analysis of Tree Growth/Streamflow Relationships

The statistical relationships between annual tree growth at CF, TR, WPP, and BB and natural streamflow were assessed by correlating each ARSTAN chronology with monthly natural streamflow series for the North Saskatchewan, South Saskatchewan, and Saskatchewan Rivers. Analyses were carried out over the period of overlap between the tree ring and natural flow data (1912 to 1992 for CF and TR; 1912 to 1996 for WPP and BB).

Reconstruction of Streamflow

Annual streamflow modeling was conducted using the transfer function approach (Fritts, 1976; Cook and Kairiukstis, 1990). This method involves the following steps. The first step is calibration of a transfer function model over the full instrumental period (the "Full" model). Multiple stepwise linear regression was used to develop a linear model to estimate the dependent streamflow variable (e.g., total annual streamflow) from a set of potential tree ring predictors, including ARSTAN chronologies in the growth year and at forward and backward lags of one, two, and three years. The inclusion of lagged predictors gives the model an autoregressive structure, which is reflective of the multiyear effect of hydroclimatic forcings on tree growth as a result of physiologic preconditioning (Fritts, 1974). The second step is verification of the "Full" model using the data splitting method of Fritts (1976). This method involves splitting the instrumental streamflow data series into halves and calibrating separate "Early" (first half) and "Late" (second half) transfer function models for each subset.

Each model is then verified over the period of independent instrumental data left out of the calibration set. In this study, the Pearson correlation coefficient, Reduction of Error (RE) and Coefficient of Efficiency (CE) verification statistics were used to test the explanatory value of the Early and Late models. Third, if the subset models pass the verification tests in the previous step, then the "Full" model is applied to the preinstrumental tree ring index series to estimate a long term record of streamflow.

RESULTS AND DISCUSSION

Tree Growth/Streamflow Relationships

Results of correlation analyses relating annual growth to monthly streamflow data are given in Table 2. Based on these results, the following observations are made:

1. All significant correlations between growth and total streamflow of individual months are positive, indicating that the climatic factors associated with high streamflow (i.e., high winter snowfall and low evapotranspiration) are also associated with wide rings.
2. *P. flexilis* chronologies show high, positive correlations with summer (June to August) streamflow. This reflects the association of winter precipitation with growth (via soil moisture recharge) and with peak streamflow (via spring runoff).
3. *P. mariana* growth is significantly correlated with Saskatchewan River streamflow during most winter months (December, February, and March) and spring (May and June), likely indicating the importance of winter precipitation and snowpack to both tree growth and streamflow.

Correlations are higher between ring widths and streamflow than between ring widths and precipitation or temperature data from stations near the sampling sites. This supports the contention that annual growth, like streamflow, is capturing and integrating a regional moisture signal (Meko *et al.,* 1995). Point measurements at climate stations contain regional climate signals. However, they also contain significant local climate signals that are not experienced or recorded by trees at distant sampling sites. Annual growth at all Alberta sites is highly correlated with late spring and summer streamflow because streamflow during this period is largely supplied by snowmelt from the Rocky Mountains, the same water source that recharges soil moisture at the beginning of the growing season.

Streamflow Reconstructions

Calibration and verification statistics for four reconstruction models that estimate total annual streamflow and pass all verification tests are given in Table 3. Models 1 and 2 predict streamflow of the North Saskatchewan River. Model 2 has a higher explained variance (48.6 percent); however, Model 1 is included (explained variance of 33.6 percent) because

TABLE 2. Significant Correlations* Between ARSTAN Chronologies and Monthly Streamflow of the North Saskatchewan (NSask), South Saskatchewan (SSask) and Saskatchewan (Sask) Rivers.

Site	River	POct	pNov	pDec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total Oct-Sep
CF	NSask									0.263	0.257			0.289
	SSask	0.337	0.250	0.240					0.404	0.416	0.363	0.323		0.462
	Sask	0.254								0.324	0.282	0.277		0.300
TR	NSask	0.455	0.412	0.332		0.254					0.361	0.244		0.419
	SSask	0.381	0.318	0.360			0.290	0.236	0.225	0.228	0.309		0.246	0.375
	Sask	0.237									0.253	0.260		0.244
WPP	NSask									0.511	0.410	0.333	0.363	0.512
	SSask		0.262			0.261				0.461	0.390	0.424	0.311	0.445
	Sask	0.271	0.287							0.317	0.532	0.466	0.448	0.445
BB	Sask			0.275		0.247	0.264		0.225	0.225				0.232

*All correlations are positive and significant at minimum p less than 0.05. Nonsignificant correlations are not shown.

TABLE 3. Calibration and Verification Statistics for Four Natural Streamflow Reconstruction Models.

Model	Dependent Variable	Potential Predictors (at t,t±1, t+2,t+3)	Length of Reconstructed Record (years)	Calibration Period	R[1]	R^2adj[2]	Verification Period	r[3]	RE[4]	CE[5]
1	North Sask. River annual streamflow at Alta-Sask border	WPP	1,113	FULL[6]	0.616	**0.336**				
				EARLY[7]	0.611	0.279	LATE	0.523*	0.258	0.256
				LATE[8]	0.736	0.472	EARLY	0.393**	0.048	0.050
2	North Sask. River annual streamflow at Alta-Sask border	CF,TR,WPP	522	FULL	0.725	**0.486**				
				EARLY	0.782	0.538	LATE	0.651*	0.386	0.387
				LATE	0.688	0.375	EARLY	0.738*	0.519	0.518
3	South Sask. River annual streamflow at Alta-Sask border	CF,TR,WPP	522	FULL	0.730	**0.480**				
				EARLY	0.796	0.559	LATE	0.692*	0.285	0.404
				LATE	0.732	0.349	EARLY	0.712*	0.254	0.222
4	Sask. River annual streamflow at Sask-Manitoba border	CF,TR,WPP,BB	325	FULL	0.811	**0.593**				
				EARLY	0.871	0.648	LATE	0.749*	0.450	0.433
				LATE	0.857	0.607	EARLY	0.639*	0.389	0.393

[1]Multiple correlation coefficient.
[2]Multiple correlation coefficient adjusted for degrees of freedom.
[3]Correlation coefficient.
[4]Reduction of Error statistic (for details see Fritts, 1976; Briffa *et al.*, 1988). Any value greater than 0 indicates value in the reconstruction.
[5]Coefficient of Efficiency statistic (for details see Fritts, 1976; Briffa *et al.*, 1988). Any value greater than 0 indicates value in the reconstruction.
[6]Calibration period extends from 1912 to 1996 for Model 1, and from 1912 to 1992 for Models 2, 3, and 4.
[7]Calibration/verification period extends from 1912 to 1954 for Model 1, and from 1912 to 1952 for Models 2, 3, and 4.
[8]Calibration/verification period extends from 1955 to 1996 for Model 1, and from 1953 to 1992 for Models 2, 3, and 4.
*Significant at minimum p less than 0.01.
**Significant at minimum p less than 0.001.

Streamflow Reconstruction Equations (Full Calibration Period):

Model 1: $3793430 + 1601567(WPP_t) + 894483(WPP_{t-1}) + 631039(WPP_{t+1}) + 734019(WPP_{t+2}) - 681775(WPP_{t+3})$

Model 2: $4297848 + 1985363(TR_t) - 1998558(TR_{t+2}) - 1000863(CF_{t-2}) + 1310678(WPP_t) + 1206329(WPP_{t-1}) + 1122718(WPP_{t+2})$

Model 3: $3764797 + 1178893(TR_{t+3}) - 2734335(TR_{t-2}) + 5738580(CF_t) - 1667761(CF_{t+1}) - 3692599(CF_{t+2}) + 28361962(WPP_{t+1}) + 1631143(WPP_{t-2})$

Model 4: $13952300 + 4924029(BB_{t-1}) + 4339814(BB_{t-3}) + 3705880(TR_t) - 6987800(TR_{t+1}) - 4983809(TR_{t+2}) - 3636826(TR_{t+3}) + 4544177(CF_t) - 3468656(CF_{t-1}) - 4810930(CF_{t-2}) + 4405086(WPP_t) + 5335087(WPP_{t+1}) + 2389742(WPP_{t-2})$

it uses only WPP chronology predictors, allowing for a proxy record length of 1,113 years. WPP alone did not produce verifiable models of streamflow for the South Saskatchewan or Saskatchewan Rivers. Model 3 predicts streamflow of the South Saskatchewan River using all three *P. flexilis* chronologies and explains 48 percent of the variance in the instrumental streamflow record. The strongest model for reconstructing Saskatchewan River streamflow (Model 4) uses all four chronologies and explains almost 60 percent of the variance in the instrumental record.

In Figure 2, actual annual streamflow for the North Saskatchewan, South Saskatchewan, and Saskatchewan Rivers are plotted with model estimated streamflow over the period of overlap (post-1910). The models capture well the interannual variability in streamflow. However, they are generally better at capturing the magnitude of the lows than the peaks. Underestimation of hydrological peaks is a common feature of tree ring reconstructions and, to some extent, occurs because there is a biological limit to the response of tree growth to high precipitation/low evapotranspiration (Loaiciga *et al.*, 1992).

The full reconstructions of streamflow are given in Figure 3. [For the North Saskatchewan River, only the longer Model 1 reconstruction is shown. Model 1 and 2 records are highly correlated at r = 0.72 ($p < 0.001$)]. The identification of hydrological drought in the three long term reconstructions was accomplished in two ways. First, the horizontal discontinuous lines

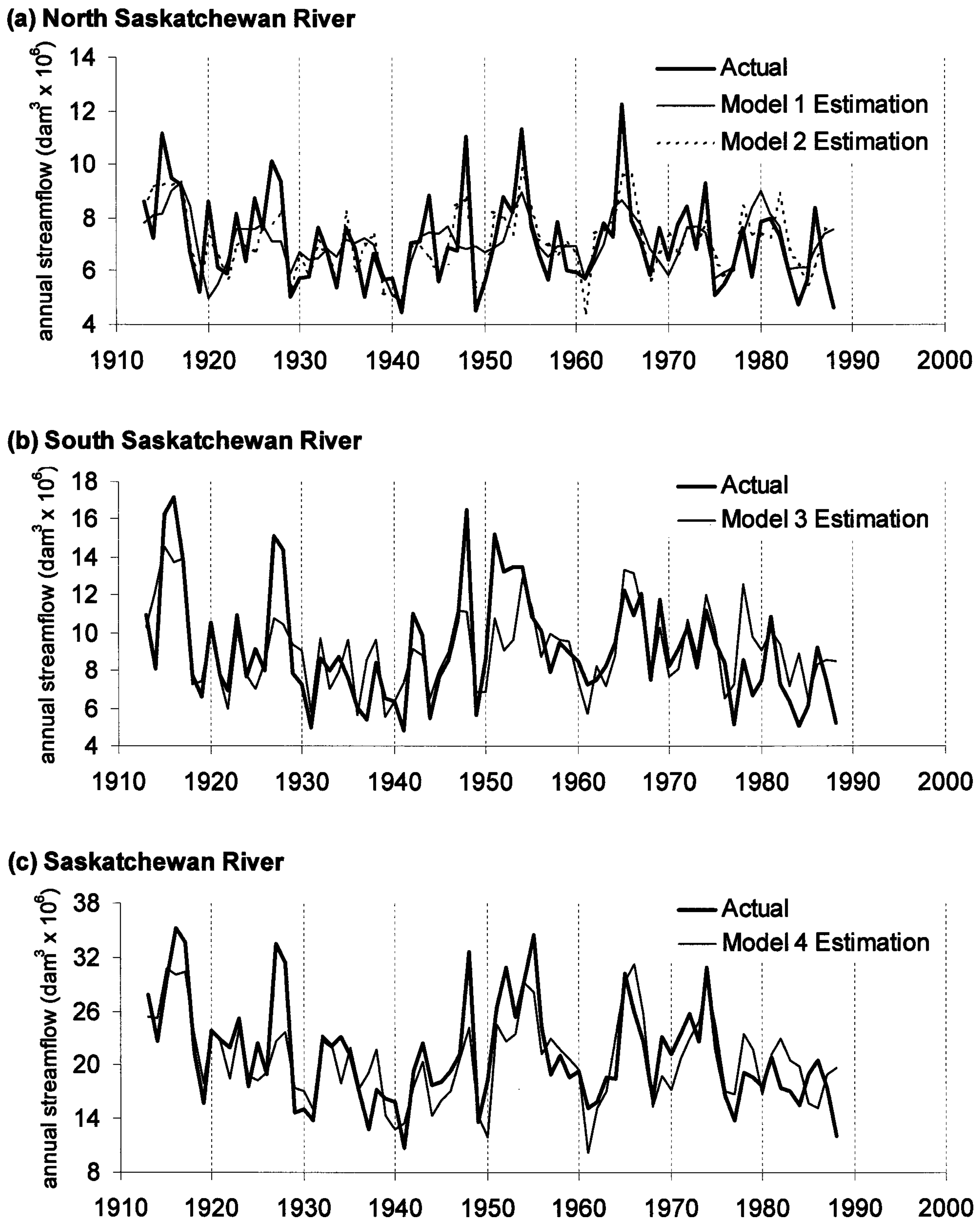

Figure 2. Actual Versus Estimated Total Annual Streamflow Over the Instrumental Period for (a) the North Saskatchewan River, (b) the South Saskatchewan River, and (c) the Saskatchewan River. Units of streamflow are dam^3 (1 dam^3 = 1,000 m^3).

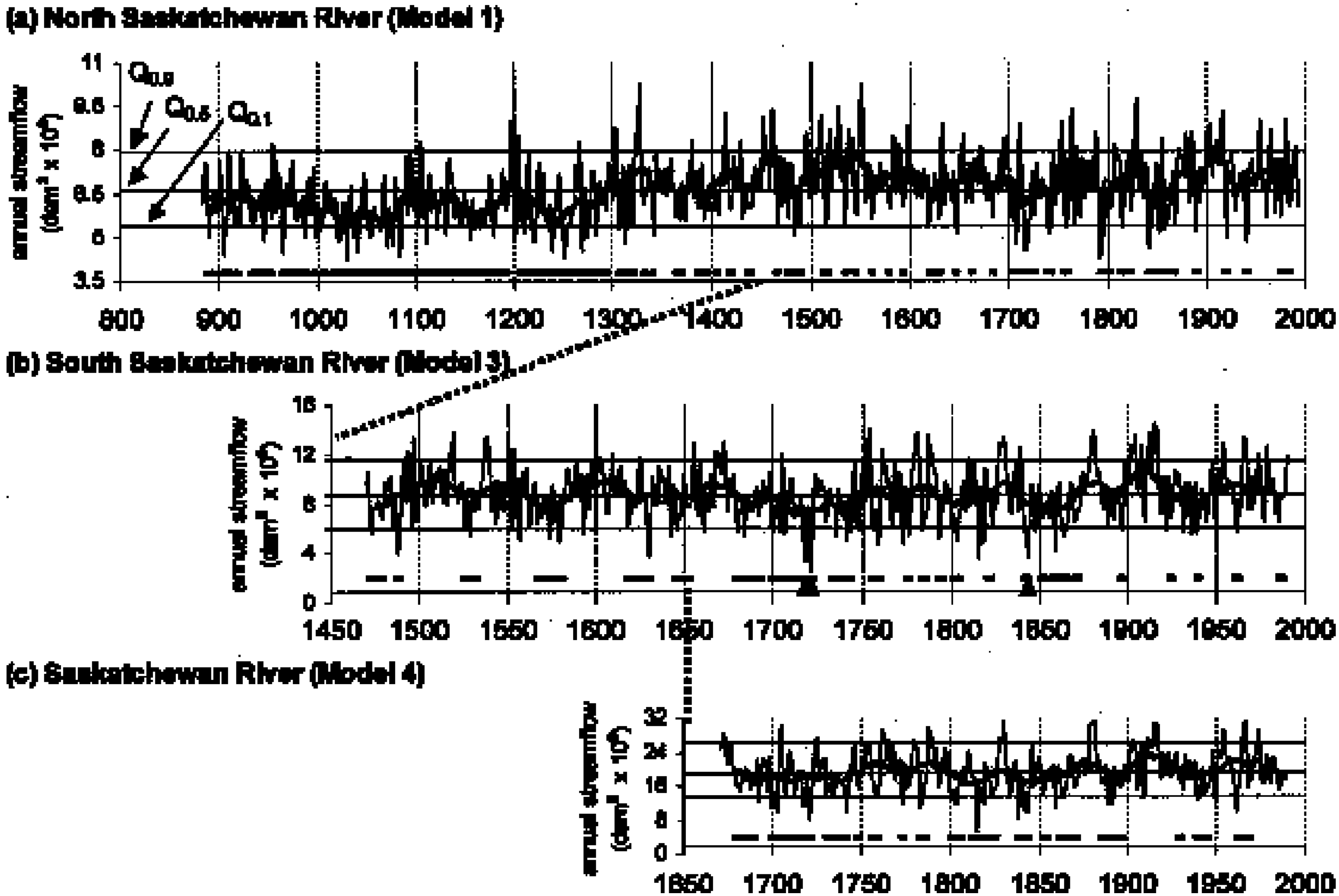

Figure 3. Long Term Reconstructions of Streamflow. Horizontal lines represent the median (0.5 quantile), 0.1 quantile, and 0.9 quantiles for each reconstruction. Reconstructions are smoothed with a 20-year moving average filter. The discontinuous line above the x-axis indicates intervals of hydrological drought (annual reconstructed streamflow less than the median for ≥ 3 years in a row). Triangle symbols in (b) indicate critical hydrological droughts (flow < 50 percent of the median for ≥ 2 years in a row).

above the x-axis represent intervals when the reconstructed annual streamflow is less than the long term median flow for three or more sequential years. This corresponds to the definition of hydrological drought used by Loaiciga *et al.* (1992) in their assessment of drought in long term streamflow reconstructions in western North America. "Critical droughts," defined by Loaiciga *et al.* (1992) as any period of at least two years when reconstructed flow is less than 50 percent of the annual median, are also indicated in Figure 3 by triangle bullets above the x-axis. Second, in Table 4, a summary of the 10 lowest single year and 5-year, 10-year, and 20-year means in reconstructed flows for each river are given. This is a simple comparative method of drought identification that allows the magnitude of historic droughts to be placed within a long term context (Meko and Graybill, 1995).

Based on the results derived by these two methods, prominent drought episodes have been identified for each river. In the 1,113-year reconstruction of North Saskatchewan streamflow, three periods of low flow are prominent: 1018 to 1045, approximately 1237 to 1260, and 1715 to 1720. The year 1793 is notable as the lowest estimated single year annual flow for the full reconstruction period. [The shorter Model 2 reconstruction (not shown) for the same river also indicates prolonged low flow in the early 1700s and the 1790s; however, in the shorter reconstruction, low flow events of the mid-1800s figure more prominently.] In the 20th Century, there were four periods of hydrological drought according to the first definition above, the lowest number of drought episodes within a century compared to the prior 10 centuries. The lowest single year flow estimated over the instrumental period (1941) ranks as the 31st lowest flow, and the lowest five-year mean flow (1940 to 1944) ranks at the 62nd lowest over the past 1,113 years. The sustained high flows in the early two decades of the 20th Century have only been exceeded by conditions in the first half of the 16th Century and in the 1460s. The long North Saskatchewan River reconstruction indicates that the frequency of low flows was higher prior to the mid-1200s (Figure 3a). During the 11th Century, there were seven hydrological droughts and only 20 years with above median streamflow, and the 12th Century records eight hydrological droughts, the longest of which is 36 years in duration (1138 to 1173). The shift from low to high streamflow conditions in the late 1200s may reflect a climate regime shift associated with a change in dominant atmospheric circulation patterns possibly initiated by changes in North Atlantic and North Pacific sea surface temperatures (Woodhouse and Overpeck, 1998).

For the South Saskatchewan River, major periods of low flow over the past five centuries were centered on the first two decades of the 1700s, the mid-19th Century, and the 1560s to 1570s. Only four periods of hydrological drought occurred during the 20th Century, compared to eight in the 19th, ten in the 18th, six in the 17th, and four in the 16th Centuries. The high flows of the early 20th Century are the highest over the full 522-year reconstruction. Three periods of "critical drought" occurred during the last 522 years, in 1843/1844, 1717/1718, and 1720/1721.

TABLE 4. Lowest Reconstructed n-Year Means for SRSB Rivers.

Rank	Single Year	5-Year	10-Year	20-Year
		MODEL 1 North Saskatchewan River (883 to 1996)		
1	1793	1249-1253	1249-1258	1024-1043
2	1030	1250-1254	1248-1257	1023-1042
3	1251	1715-1719	1250-1259	1025-1044
4	906	1248-1252	1247-1256	1022-1041
5	1084	1251-1255	1251-1260	1021-1040
6	1269	1714-1718	1022-1031	1020-1039
7	965	904-908	1023-1032	1019-1038
8	1042	1716-1720	1246-1255	1237-1256
9	1238	1792-1796	1021-1030	1026-1045
10	1716	1237-1241	1035-1044	1018-1037
		MODEL 3 South Saskatchewan River (1470 to1992)		
1	1721	1717-1721	1713-1722	1702-1721
2	1720	1718-1722	1714-1723	1706-1725
3	1717	1716-1720	1715-1724	1841-1860
4	1815	1840-1844	1711-1720	1840-1859
5	1844	1841-1845	1716-1725	1705-1724
6	1630	1485-1489	1717-1726	1704-1723
7	1488	1800-1804	1573-1582	1707-1726
8	1718	1714-1718	1572-1581	1562-1581
9	1859	1719-1723	1841-1850	1561-1580
10	1843	1814-1818	1809-1818	1701-1720
		MODEL 4 Saskatchewan River (1671 to 1996)		
1	1815	1839-1844	1836-1845	1800-1819
2	1838	1698-1703	1835-1844	1799-1818
3	1721	1717-1721	1712-1721	1801-1820
4	1842	1838-1842	1838-1847	1837-1856
5	1703	1698-1703	1837-1846	1803-1821
6	1741	1737-1741	1815-1824	1836-1855
7	1844	1840-1844	1713-1722	1833-1852
8	1961	1957-1961	1814-1823	1838-1857
9	1843	1839-1843	1733-1742	1806-182
10	1700	1696-1700	1732-1741	1798-1817

The Saskatchewan River presents a very similar record to that of the South Saskatchewan River: 20th Century streamflow is relatively high within a long term context, and the most extreme hydrological drought conditions recorded (i.e., the prolonged hydrological droughts of the first half of the 1700s) have not been experienced over the historic period.

In Figure 4, the streamflow reconstructions are smoothed with a 20-year moving average and plotted together over their period of overlap. The highest correlation is between the South Saskatchewan and Saskatchewan River reconstructions ($r = 0.84$; $p < 0.001$). Correlations between the North Saskatchewan and Saskatchewan River records and between the North and South Saskatchewan River records are 0.58 ($p < 0.001$) and 0.60 ($p < 0.001$), respectively. Similarities in the chronologies are expected, given that the reconstruction models share some predictors and that the rivers share a common source area. Most major drought years are coincident in the North Saskatchewan, South Saskatchewan, and Saskatchewan Rivers. Most notably, single year droughts in 1961, 1941, 1891, 1844, and 1816 appear in all records. On the North and South Saskatchewan Rivers, there are also coincident hydrological droughts in 1759, 1720, 1631, and 1580.

The 20th Century appears to be typified by relatively high flows. For example, 20th Century mean flows are 8.6, 6.5, and 8.5 percent higher than the long term means on the North Saskatchewan, South Saskatchewan, and Saskatchewan Rivers, respectively (Table 5). Annual reconstructed streamflow on all three rivers has remained above the median since the 1950s. The high flows in the early 1900s are also apparent and, in the case of the South Saskatchewan, unprecedented.

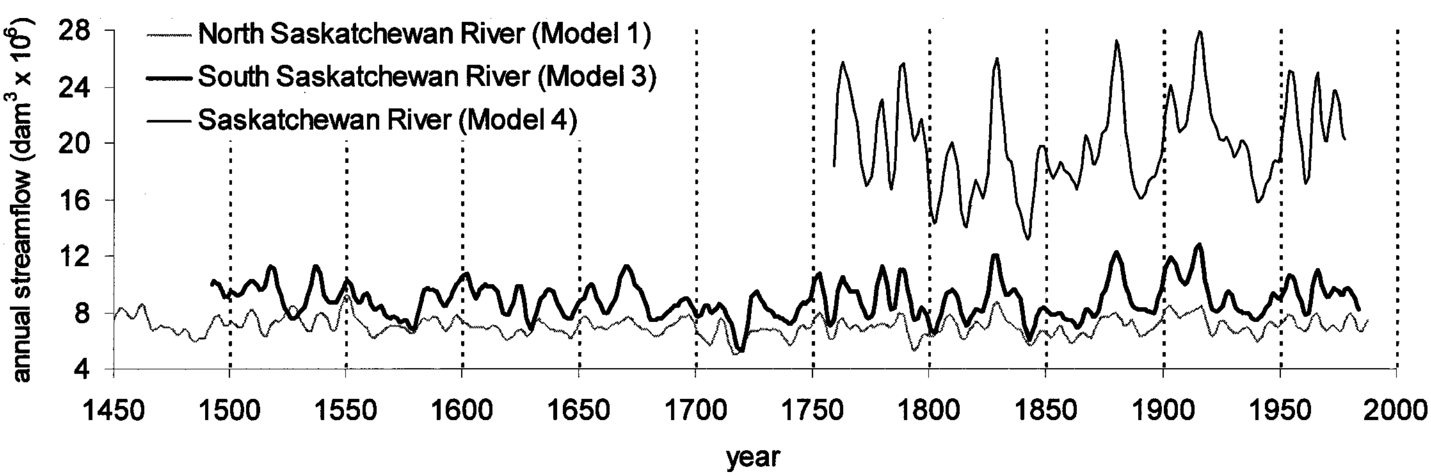

Figure 4. Reconstructions of Total Annual Streamflow of SRSB Rivers. All series are smoothed with 20-year moving average filters.

TABLE 5. Comparison of Actual and Reconstructed Annual Streamflow Means (units are dam^3).

Interval	North Saskatchewan	South Saskatchewan	Saskatchewan
A. 1913 to 1967 Instrumental Mean*	7,283,871	9,555,831	21,939,363
B. 20th Century Reconstructed Record Means	7,220,175	9,410,631	20,925,304
C. Mean of Full Reconstruction	6,649162	8,839,131	19,284,324
	(Model 1)	(Model 2)	(Model 4)
Percentage Difference (B-C)/C	+ 8.6	+ 6.5	+ 8.5

*Interval used for apportionment purposes according to the Prairie Provinces Master Agreement on Apportionment (1969).

Comparison With Other Records

Historical records of flood and low flow events on Prairie rivers are scarce and limited to the past two centuries (Catchpole, 1978). However, some anecdotal documentation of streamflow exists that can be compared with the dendrohydrological reconstructions presented here. For example, in an assessment of Hudson's Bay and North West Company documents dating from the first decade of the 19th Century, Kemp (1982, p. 36) found that in 1804 and 1805, "drought was reported from the Upper Missouri in the west to Lake Nipigon in the east and low water retarded the progress of the canoe brigades throughout the area." Although this hydrological drought was most severe on the Assiniboine and Red Rivers in the Canadian Prairies, our reconstructions show flows well below the 0.1 quantile on the South Saskatchewan and Saskatchewan Rivers at this time (Figure 3).

Meteorological droughts over the 1815 to 1819 period are well known from records of crop failure and grasshopper infestation at the Red River Settlement in southern Manitoba (Hope, 1938; Allsopp, 1977). During this period, journal reports of low streamflow are also frequent (Ball, 1992). As an example, Peter Fidler, an employee of the Hudson Bay Company at Brandon House, Manitoba (now Brandon), reported in 1819 that "all small creeks that flowed with plentiful streams all summer have entirely dried up, for these several years loaded craft could ascend up as high as the Elbow or Carlton House but these last 3 summers it was necessary to convey all the goods from the Forks by land in carts . . ." (in Ball, 1992, p. 189). Low flows during the same period on the Saskatchewan River are also frequently mentioned in Hudson's Bay Company employee journals (Ball, 1992). The reconstruction of Saskatchewan River streamflow shows major hydrological drought events in 1815 and 1817; in fact, the single year drought of 1815 is the lowest flow of the full 325-year period. The South Saskatchewan River shows similarly low flows in 1815 and 1817. On the North Saskatchewan River, flows were near median levels in 1815 to 1818. However, a hydrological drought occurred in 1819. In general, for the 1815 to 1819 period, both the historical and tree ring data support the existence of hydrological drought.

There is ample historical documentation of meteorological drought during the mid-1800s across the northern Great Plains (e.g., Mock, 1991; Blair and Rannie, 1994). Tree ring reconstructions of precipitation have also indicated drought during the mid-19th Century in the southern Canadian Prairies (Sauchyn and Beaudoin, 1998), Rocky Mountain foothills (Case and MacDonald, 1995), and Montane regions (Watson and Luckman, 2001) and during the 1940s in southern Manitoba (St. George and Nielsen, 2002). The SRSB streamflow reconstructions indicate that hydrological drought was also frequent during this time. On the South Saskatchewan River, critical drought and low flow occurred in 1843 and 1844, and the years between 1841 and 1873 show annual streamflow below the long term median. Evidence of low snowfall on the eastern Rocky Mountain slopes during the mid-1800s is found in the dendrohydrological reconstruction of Lake Athabasca water levels of Stockton and Fritts (1973). Over the interval of 1810 to 1967, the lowest reliable 20-year mean lake levels occurred over the period 1861 to 1880. Since one of the major rivers draining into the lake, the Athabasca River, has its headwaters in the southern Canadian Rocky Mountains, the lake level reconstruction to some extent captures the same signal as the SRSB records. The lake level record also shows low levels between 1810 and 1820 and high levels in the 1820s and early 1900s, all of which are prominent features of the Prairie river reconstructions. The decline in streamflow evident for the South Saskatchewan system around 1800 also corresponds in general timing with the reactivation of sand dune systems in southern Saskatchewan (Wolfe *et al.*, 2001).

Paleoclimatic records for drought variability in the adjacent western United States are available from a number of sources (see Woodhouse and Overpeck, 1998). Recent dendrohydrological work in the Colorado Front Ranges (Woodhouse, 2001) shows similarities with the SRSB records. Most notably, reconstructions from Colorado also show fewer low flow episodes over the 20th Century compared with the preceding 200 years and a period of dry conditions and low flows during the 1840s. The dry period of the mid-1800s appears to have extended over large portions of the western United States and to have affected flow in the Colorado River basin west of the continental divide (Cook *et al.*, 1999; Woodhouse, 2001). There is much tree ring evidence for a very severe and prolonged drought in Mexico and the western United States in the late 16th Century (Stahle *et al.*, 2000) and coincident extremely low flows in the Colorado River (Stockton and Jacoby, 1976; Hidalgo-Leon *et al.*, 2000). However, this drought does not appear to have propagated far enough northward to severely affect the flow of the Canadian Prairie rivers. Precipitation reconstructions for the Canadian Rocky Mountains and foothills and for southern Manitoba also provide little evidence for an exceptionally prolonged meteorological drought during this period (Case and MacDonald, 1995; Luckman and Watson, 1998; Watson and Luckman, 2001; St. George and Nielsen, 2002).

Prolonged low flow conditions over the period of approximately 900 to 1300 are coincident with evidence of prolonged dry conditions across much of western North America obtained from the analysis of lake sediments, plant macrofossils, tree rings, archaeological records, eolian sedimentary records, and alluvial records (e.g., Stine, 1994; Forman *et al.*, 1995; Muhs and Holliday, 1995; Grissino-Mayer, 1996; Hughes and Graumlich, 1996; Laird and Cumming, 1996; Dean, 1997; Laird *et al.*, 1998; Woodhouse and Overpeck, 1998; Fritz *et al.*, 2000; Meko *et al.*, 2001). In many cases, these records show episodic events of prolonged drought rather than continuous dry conditions during the period. Geographically, it appears that episodic prolonged dry conditions during this period may have extended from Alberta to Minnesota and southward to parts of California and the southwestern United States. The geographic extent, duration, and, in some regions, magnitude of this generally arid period may have been greater than those of the late 16th Century megadrought described by Stahle *et al.* (2000). Cooler temperatures in the North Atlantic and resulting shifts in atmospheric circulation have been suggested as a causal mechanism for this episode of prolonged dry conditions (Woodhouse and Overpeck, 1998). This is a paleohydrological event that requires much additional scrutiny.

CONCLUSIONS

Information regarding natural hydrological variability and potential extremes in hydrological drought duration and magnitude in the Saskatchewan River subbasin is important for the effective planning and management of surface water resources in the Prairies. Managers should consider the fact that, over the instrumental period, annual streamflow on the North Saskatchewan, South Saskatchewan, and Saskatchewan Rivers has been relatively high within a long term context. The period used to determine water apportionment (1912 to 1967) under the PPWB Master Agreement on Apportionment shows a mean annual flow even higher than the 20th Century mean (Table 5). In addition, hydrological droughts of the 1940s, while the worst of the 20th Century, are not representative of the most extreme low flow conditions possible.

High mean 20th Century flow for the three rivers considered in this study may be attributable to higher precipitation in the Rocky Mountains as a result of regional warming. However, reconstructions of annual streamflow may mask seasonal trends related to global warming. Many scenarios predict that increasing temperatures will result in decreasing May to July flows due to earlier snowmelt and increasing flows in the fall due to more precipitation falling as rain versus snow (Burn, 1994; Leith and Whitfield, 1998). These trends would be cancelled out in the summation of annualized flow. Future dendrohydrological analyses for the region should focus on reconstructing seasonal flow in order to investigate long-term trends in seasonal streamflow. Further statistical analysis of aspects of variability in the time series most important to water resource managers is also needed (e.g., Touchan *et al.*, 1999).

The current drought, which is already testing the adequacy of the PPWB Master Agreement on Water Apportionment, is not as severe as some earlier prehistoric drought episodes in terms of the magnitude or duration of low streamflow in the Saskatchewan River system. It is almost certain that any current water management options would not mitigate the impact of a widespread and sustained severe drought such as that evident in the SRSB reconstructions and other proxy climate records for the period of approximately 900 to 1300. The occurrence of such a hydrological drought would have serious implications for water resource allocations in both Canada and the United States.

The tree ring reconstructions presented here illustrate the usefulness of tree rings for providing long term streamflow records in central Canada. They also highlight the risks involved if future water policy and infrastructure development are based on streamflow variability over the historical record.

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