Research paper

Alternative standardization approaches to improving streamflow reconstructions with ring-width indices of riparian trees

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Abstract

Old, multi-aged populations of riparian trees provide an opportunity to improve reconstructions of streamflow. Here, ring widths of 394 plains cottonwood (*Populus deltoides*, ssp. *monilifera*) trees in the North Unit of Theodore Roosevelt National Park, North Dakota, are used to reconstruct streamflow along the Little Missouri River (LMR), North Dakota, US. Different versions of the cottonwood chronology are developed by (1) age-curve standardization (ACS), using age-stratified samples and a single estimated curve of ring width against estimated ring age, and (2) time-curve standardization (TCS), using a subset of longer ring-width series individually detrended with cubic smoothing splines of width against year. The cottonwood chronologies are combined with the first principal component of four upland conifer chronologies developed by conventional methods to investigate the possible value of riparian tree-ring chronologies for streamflow reconstruction of the LMR. Regression modeling indicates that the statistical signal for flow is stronger in the riparian cottonwood than in the upland chronologies. The flow signal from cottonwood complements rather than repeats the signal from upland conifers and is especially strong in young trees (e.g. 5–35 years). Reconstructions using a combination of cottonwoods and upland conifers are found to explain more than 50% of the variance of LMR flow over a 1935–1990 calibration period and to yield reconstruction of flow to 1658. The low-frequency component of reconstructed flow is sensitive to the choice of standardization method for the cottonwood. In contrast to the TCS version, the ACS reconstruction features persistent low flows in the 19th century. Results demonstrate the value to streamflow reconstruction of riparian cottonwood and suggest that more studies are needed to exploit the low-frequency streamflow signal in densely sampled age-stratified stands of riparian trees.

Keywords

age growth, cottonwood, dendrohydrology, detrending, 'Little Ice Age', Little Missouri River

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Introduction

Tree-ring reconstructions of streamflow contribute to understanding of hydroclimatic variability on long time scales (see review by Loaiciga et al., 1993) and have been applied directly as inputs to river management models to test the resilience of supply systems to severe droughts not represented by the gauged flow record (e.g. Harding et al., 1995; Phillips et al. 2009; Prairie et al., 2008; Meko et al., 2012). Flow reconstructions typically use ring widths of upland rather than riparian trees, and a conceptual model that both runoff and tree growth are positively related to net precipitation, or precipitation minus evapotranspiration (Meko et al., 1995; Schulman, 1945).

Riparian trees, useful for information on flood history and changes in channel morphology (e.g. Ballesteros et al., 2010; Everitt, 1968; Yanosky and Jarrett, 2002), have generally been avoided in such reconstructions. Longer lived tree species and specimens on well-drained soils favoring ring-width sensitivity to soil moisture are often available from upland locations. Riparian areas moreover are often poorly drained and heavily impacted by human activity, including roads, agriculture, flow regulation, and industrial and residential development, which can obscure the relation between flow and ring width.

Despite these drawbacks, riparian trees have certain potential strengths for use in streamflow reconstruction, especially where anthropogenic disturbance is minimal. Soil moisture in the root zone of riparian trees is directly influenced by fluctuating water levels in the river through flooding or recharge of shallow groundwater reservoirs (Reily and Johnson, 1982; Rood et al., 2013), and ring width is often strongly influenced by flow (Clark, 1987; Liu et al., 2007; Stromberg, 2001; Stromberg and Patten, 1990). Riparian forests often include a wide range of tree ages, making it possible to distinguish the effects of age and climate variation (Everitt, 1968; Merigliano et al., 2013). Furthermore, in dry regions (e.g. USA Great Plains), riparian ecosystems often include some of the oldest trees in the landscape, and growth of these trees is often

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limited by moisture availability (Edmondson et al., 2014). Riparian tree rings could yield streamflow information that complements rather than duplicates the information available from ring widths of drought-sensitive upland trees. For example, rainfall events may recharge soil moisture in the root zones of upland trees but be insufficient to produce appreciable runoff and streamflow. Or rainfall events on saturated soil in upper parts of the watershed may run off without influencing the growth of upland trees, while moderating growth of riparian trees through local effects (e.g. flooding followed by recharge of shallow aquifers).

In this paper, we explore the signal for seasonal-total streamflow in a collection of tree-ring data from 394 plains cottonwood (*Populus deltoides*, ssp. *monilifera*) trees growing in a relatively undisturbed setting along the Little Missouri River (LMR) in the North Unit of Theodore Roosevelt National Park (THRO), North Dakota (Figure 1). A tree-ring chronology extending back to 1643, and considered robust back to the 1740s, developed from these cottonwoods was previously shown to correlate strongly with annual precipitation summed over months August–July and with June–July Palmer Drought Severity Index (PDSI) (Edmondson et al., 2014). This work follows up with examination of the same set of cottonwood ring-width measurements from a hydrologic perspective. We address the value of riparian tree-ring data to streamflow reconstruction when long drought-sensitive conifer chronologies are also available from nearby upland sites and explore alternative tree-ring standardization strategies as a way to enhance the low-frequency (e.g. centennial-and-longer wavelengths) streamflow reconstruction signal. We also address the possible value of age stratification to enhancing the cottonwood signal for streamflow. Finally, we generate two alternative flow reconstructions that use tree-ring data from both cottonwood and upland conifers and suggest possible reasons for observed differences in reconstructed flow.

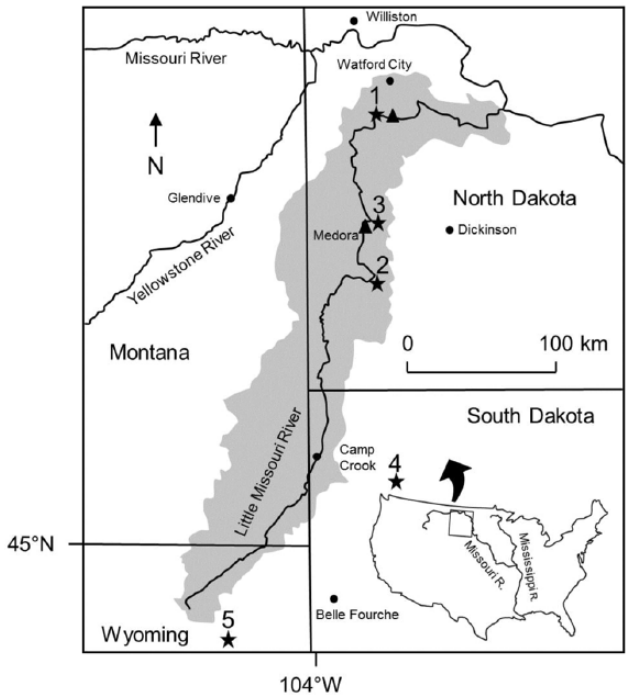

Figure 1. Map showing location of stream gages along the Little Missouri River (triangles), tree-ring sites (stars), and watershed of Little Missouri River. Tree-ring sites are (1) *Populus deltoides*, ssp. *monilifera* at North Unit of Theodore Roosevelt National Park, (2) *Pinus ponderosa* at Burning Coal Vein, (3) *Juniperus scopulorum* at South Unit of Theodore Roosevelt National Park, (4) *P. ponderosa* at Eagle Nest Canyon, and (5) *P. ponderosa* at Devil's Tower National Monument. File names of sites 2–5 in the International Tree-Ring Data Bank are nd001, nd006, sd008, and wy034, respectively.

Data and methods

The primary tree-ring data for this study consist of measured ring widths of 394 cottonwood trees on the floodplain of an 18-km stretch of the LMR in the North Unit of THRO, North Dakota (47°35′N, 103°23′W). The climate in the watershed is semiarid (Edmondson et al., 2014). Peak flow usually occurs in late March or early April as a result of snowmelt and can be augmented by ice jams. In some years, the annual peak occurs later as a result of rainfall, especially in May and June. The river can cease to flow in the late summer. Cores were collected from the nearest cottonwoods to randomly selected points on the floodplain (Edmondson et al., 2014). The collection, cross-dating, and measurement of the samples have been described by Edmondson et al. (2014). All samples are from living trees, were collected in 2010, and have complete rings (measurement interval) through 2009 or 2010. At least two cores were taken from each tree to facilitate cross-dating and to ensure that at least one core was close to pith. Using the core closest to pith from each tree, the number of additional years to pith was estimated by dividing the radius of curvature of the innermost ring boundary by the average width of the four innermost rings.

We generated three versions of the site chronology from these same ring-width data to study the relationship between tree growth and the flow of the LMR. The first two versions, which we call 'age-curve-standardized', or ACS, were computed by a procedure combining elements of regional curve standardization (RCS; Briffa et al., 1992) and age-banding (Briffa et al., 2001). The first step for ACS chronologies is to align the ring-width series at their pith year (actual or estimated) and compute a mean ring width as a function of age. A smooth curve is then fit to this plot of mean ring width, and the individual ring-width series are converted to indices by dividing widths by the expected width for a given age. We estimate the smooth curve by locally weighted regression, or loess (Cleveland, 1979; Martinez and Martinez, 2002, 2005), with constraints explained in the context of the results (see below). Next, the core indices are shifted back to their original calendar years; the site chronology for a given year is computed as the average over core indices available in that year. Two different ACS chronologies, with membership restricted to ring age ranges 5–35 years and 36–165 years were generated. These particular age ranges were selected considering the sample depth (number of trees) available for estimating a curve of expected ring width as a function of ring age. The dividing point at 35/36 years is somewhat arbitrary, but allows for the investigation of differences in hydroclimatic response of old and young cottonwoods. These two ACS chronologies are mutually exclusive in that no rings that contribute to the young-tree chronology contribute to the older tree chronology, and vice versa. In this system, cottonwood recruitment occurs next to the channel (Everitt, 1968; Miller and Friedman, 2009), and the channel migrates away over time. We hypothesized that the proximity of the young trees to the channel may lead to a stronger flow–growth relationship in young cottonwoods than in old cottonwoods.

Another cottonwood chronology, which we call 'time-curve-standardized', or TCS, was computed by the conventional method (e.g. Fritts, 1976) of detrending cores individually by fitting and removal (ratio method) of a curve of ring width against time, with no consideration of the biological age of the rings. Long ring-width series (longer than about 100 years) were selected for the TCS cottonwood chronology to avoid complications associated with the 'segment-length curse' (Cook et al., 1995), and the core ring-width series were detrended with a cubic smoothing spline with frequency response of 0.50 at two-thirds the length of series (Cook and Peters, 1981). Standardization included

computation of a time-varying expressed population signal (EPS) (Wigley et al., 1984) to identify when the sample size becomes adequate to capture the population tree-ring signal and variance stabilization (Osborn et al., 1997) to reduce possible distortion of the site chronology by the time-varying sample size (number of cores). Additional details of the ACS and TCS procedures are provided in the Supplementary Material (file S2, available online).

Besides the cottonwood data, tree-ring data from four upland conifer sites near the LMR watershed were also used in this study. Ring widths (rwl files) were downloaded from the International Tree-Ring Data Bank (ITRDB) (http://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring) for the following ITRDB sites: nd001, nd006, sd008, and wy034 (Figure 1). Burning Coal Vein (nd001) is a *Pinus ponderosa* Douglas ex C. Lawson site at elevation 790 m along the LMR. THRO (nd006) is a *Juniperus scopulorum* Sarg. site at elevation 760 m. Eagle Nest Canyon (sd008) is a *P. ponderosa* site at elevation 1090 m. Devils Tower National Monument (wy034) is a *P. ponderosa* site at elevation 1319 m in the Black Hills. The tree-ring data for the upland chronologies, with the exception of wy034, were collected and developed by the primary author. The data for site wy034 were collected by MC Stambaugh. Tree-ring chronologies from the four conifer sites are part of the tree-ring network used to generate the North American Drought Atlas (Cook et al., 1999, 2004). Chronologies from three of the sites (nd001, nd006, and sd008) have previously been applied in various regional studies of drought history in the western Great Plains (Meko, 1992; Sieg et al., 1996; Stockton and Meko, 1983). Ring-width series for each conifer site were screened using the program COFECHA (Grissino-Mayer, 2001; Holmes, 1983) and were quality-controlled with time series plots to eliminate short series and to truncate or eliminate series with weak inter-series correlation. TCS chronologies were then computed using the same screening and detrending rules as used for the TCS cottonwood chronology described previously.

Principal components analysis (using the correlation matrix) was then run on the four standard chronologies for their common period, 1651–1990, and the score time series of the first component (PC1) was used in this study as the proxy representing upland conifers. PC1 explains 64% of the variance of the four conifer chronologies. Files with the culled ring-width data, the site chronologies, and scores of PC1 are included in the Supplementary Material (files S3 and S6, available online).

The primary streamflow data used in this study were monthly average discharges of the LMR near Watford City, North Dakota (U.S. Geological Survey Gage 06337000; Figure 1). Flow data were downloaded from the U.S. Geological Survey (http://waterdata.usgs.gov/nwis/nwisman/?site_no=06337000&agency_cd=USGS). The drainage area above the gage, located about 7 km downstream from the cottonwood site, is 21,514 km^2 and includes plains and foothills, but no mountains, with the highest elevation being about 1400 m near the southern basin boundary. The gaged flow record near Watford City is complete for water years 1935 to present. For the period 1935–2010, the mean average daily flow was 15.11 m^3/s for the water year and 26.42 m^3/s for April–July. Data for this gage were used to study the relationship between flow and tree rings, and as calibration and main validation data (cross-validation) for flow reconstructions. Exploratory correlation analysis and scatterplots indicated that the April–July period was optimal for strength of relationship between flow and tree rings, and subsequent analyses use flow totaled over that spring to early-summer interval.

Scattered flow data for a gage upstream at Medora (U.S. Geological Survey Gage. 06336000) were available for a spot check of agreement of reconstructions with flows prior to 1935. For this check, monthly flows for the gage at Medora were converted by regression models into estimates of monthly flows for the gage near Watford City. Data and statistics for the regression models are provided in the Supplementary Material (files S4 and S5, available online). The Medora data provided estimates of flow for 12 non-contiguous water years before the start of the gage record near Watford City. Although there are numerous local agricultural diversions along the LMR, there are no large dams or diversions in the watershed. As a result, peak flow, mean annual flow, and flow timing have been relatively unaffected by water management. Flow and its measurement can be affected at these gages by ice in December through April, but uncertainty related to ice has a relatively small effect on annual and seasonal totals.

Scatterplots of April–July total volume flow of the LMR near Watford City (henceforth, 'flow') on tree-ring chronologies were used to assess the need for transformation of flow ($\log_{10}$ or square-root). The strength of the linear relationship between the chronologies and flow was summarized by correlation, whose significance was evaluated by a *t*-test (Haan, 2002), after adjustment of degrees of freedom for first-order autocorrelation of the individual time series (Dawdy and Matalas, 1964). The adjustment of degrees of freedom was applied only if both series had significant positive lag-1 autocorrelation at $\alpha = 0.05$ by a one-tailed test (Chatfield, 2004).

Alternative reconstructions were generated by stepwise multiple linear regression (Weisberg, 1985) of flow on combinations of tree-ring data from upland conifers and riparian cottonwoods and were compared with a reconstruction based on only the upland conifers. Alternative combined models with PC1 of conifers and either the ACS young-tree or TCS version of the cottonwood chronology were investigated. The relative importance of predictor variables in each reconstruction model was measured by standardized regression coefficients. Regression assumptions were checked by analysis of residuals (Weisberg, 1985), reconstruction models were validated by cross-validation (Michaelsen, 1987), and validation skill was measured by the reduction of error (RE) statistic (Fritts et al., 1990).

Results

The plot of cottonwood mean ring width as a function of ring age has three distinct segments (Figure 2). Mean width increases over the first few years (1–5) of tree growth, peaks at age 5–15 years, and then declines steadily to about age 165 years. Above ring age 165 years, mean width is erratic (Figure 2a), reflecting the small sample size for the oldest ring ages (Figure 2b). Moreover, the part of the plot of mean ring width on ring age for the oldest rings is susceptible to climatic bias because the oldest rings (furthest from pith) necessarily sample only the most recent years. For example, our collection includes no trees that reached an age of 250 before 1890. Accordingly, a smooth loess curve was fit to ring ages 5–165 years, the part of the mean ring series based on a relatively large sample size representing a broad range of calendar years. Younger and older rings were omitted from the ACS chronologies.

A scatterplot matrix shows variable strength of the linear relationship of flow with tree-ring series depending on version of tree-ring series and transformation of flow (file S9 in the Supplemental Material). The correlation is highest ($r = 0.68$) for the young-ring ACS cottonwood chronology and $\log_{10}$-transformed flow. The correlation is highly significant ($p < 0.001$) for all series examined and is lowest ($r = 0.59$) for PC1 of the conifer chronologies. Relationships are highly heteroscedastic (higher scatter for higher flows) for untransformed flows and much less so for transformed flows.

Results of regression analysis indicate that cottonwood complements rather than duplicates the tree-ring signal of upland conifers for April–July flow (Table 1). Two alternative reconstruction models, RecACS + PC1 and RecTCS + PC1, were generated. Each

model has a 1935–1990 calibration period and includes PC1 of the conifers as one of its two predictors. RecACS+PC1 has the young-tree ACS cottonwood as the second predictor, and RecTCS+PC1 has the conventional, or TCS, cottonwood chronology as its other predictor. In both models, the cottonwood predictor enters first in a stepwise selection. Highest calibration accuracy (R^2=0.57) is achieved by RecACS+PC1. Adjusted R^2 for that model is 0.24 higher than for a model using just conifer PC1. The relative sizes of standardized coefficients on the two predictors in each model verify the greater contribution from cottonwood than from conifers to the reconstructed flow.

Reconstructions by RecACS+PC1 and RecTCS+PC1 closely track observed flows over the 1935–1990 calibration period (Figure 3). No clear difference is evident in the low-frequency components of the two reconstructions during the calibration period. The slightly higher R^2 of RecACS+PC1 is reflected in closer agreement of reconstructed and observed flows in individual years (e.g. 1935–1939, 1947, 1952, 1980), although in some years RecTCS+PC1 is closer than RecACS+PC1 to the observed (e.g. 1941, 1944). The extended observed flow record for Watford City estimated from observed flows at Medora shows RecACS+PC1 closer to observed flow in 1929 and RecTCS+PC1 closer to observed flow in 1904, 1905, 1906, and 1930. Chronology statistics indicated that by the 1740s, the TCS cottonwood chronology and each of the four conifer chronologies had reached an EPS of 0.85. EPS for one of the conifer chronologies (Devils Tower) drops to 0.75 in the 20th century, but because PC1 is a weighted average over four sites, the sample size for the TCS predictors in reconstruction models RecACS+PC1 and RecTCS+PC1 is probably adequate for climatic interpretation at least back to the 1740s.

RecACS+PC1 is much drier than RecTCS+PC1 before the start of the 20th century (Figure 4). Before the mid-1800s, this difference defies interpretation because of the small sample size of the young-tree ACS cottonwood chronology (Figure 5b). After about 1840, however, the sample size of the young-tree cottonwood chronology is greater than 50 trees, while the difference in reconstructed means of RecACS+PC1 and RecTCS+PC1 is large (Table 2). While regression guarantees equivalence of reconstructed and observed means for the calibration period of the model, no such constraint is imposed on means before the start of the calibration period. For 1840–1900, the mean of RecACS+PC1, after back-transforming from log units to flow volume as cubic meters, is only 60% of the mean of RecTCS+PC1 (144×10^6 m^3 vs 241×10^6 m^3). Reconstructed flows and listings of predictand and predictors for the RecACS+PC1 and RecTCS+PC1 regression models are included in the Supplementary Material (files S6 and S7, available online).

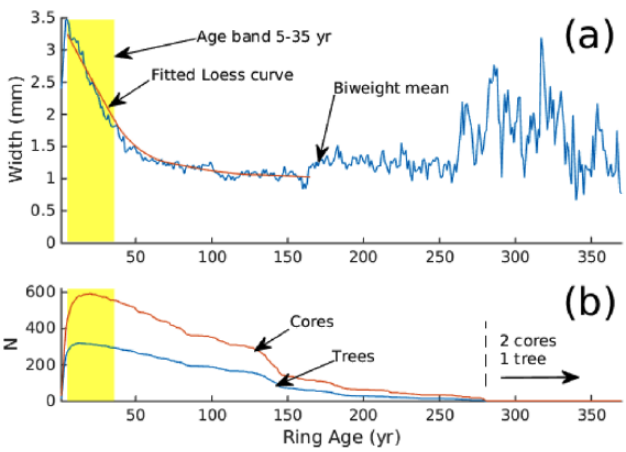

Figure 2. Time plots of data for generation of age-curve-standardized (ACS) cottonwood chronology: (a) mean ring width as function of estimated ring age and (b) sample size as function of estimated ring age. The biweight mean (solid jagged line) of ring width as a function of ring age for ages 5–165 years is fit with a piecewise linear local regression, or loess (smooth solid line). Smooth curve for rings younger than 5 years is computed as the median of widths. Shading marks range of ring ages (5–35 years) for generating young-tree ACS chronology.

Discussion and conclusion

Results demonstrate that ring widths of riparian cottonwood have a sufficiently strong flow signal to be used either alone or in combination with upland tree-ring chronologies for reconstruction of LMR flow, and that time series features of reconstructed flow are sensitive to method of processing the cottonwood ring widths into a site chronology. Detrending with a single curve assumed to represent expected ring width as a function of age is attractive for potentially retaining low-frequency information generally removed in traditional chronology development. Restricting this ACS chronology to young trees is consistent with a conceptual model that young cottonwood trees would be in a favorable hydrologic setting next to the channel to sense changes in flow. Results indicate a relatively high correlation with flow for such an age-stratified ACS chronology.

At the annual to decadal scale, our two flow reconstructions are similar to each other and consistent with other reconstructions of flow in the region (Figure 6). Rings of burr oak (*Quercus macrocarpa*) were used to reconstruct flows back to 1726 in

Table 1. Regression statistics for alternative reconstruction models.

Model[a]	Coefficients[b]			Statistics[c]			
	a	*b*1	*b*2	R^2_{adj}	Δ	RE	RMSE
RecACS+PC1	7.507	0.698 (0.53)	0.104 (0.38)	0.57	0.24	0.56	0.287
RecTCS+PC1	7.475	0.872 (0.43)	0.093 (0.34)	0.45	0.12	0.42	0.329
RecPC1	8.335	N/A	0.159 (0.25)	0.33	0	0.32	0.356
RecACS	7.260	0.889 (0.68)	N/A	0.45	0.12	0.41	0.323
RecTCS	7.073	1.265 (0.63)	N/A	0.38	0.05	0.30	0.346

RE: reduction of error; RMSE: root-mean-square error.
[a]All models are calibrated on years 1935–1990. The predictand is log-transformed April–July total flow (original data in m^3). Predictor 2 for all models is the first principal component (PC1) of four conifer chronologies. Predictor 1 is the cottonwood 5–35 years' ACS site chronology (RecACS and RecACS+PC1), the spline-detrended TCS cottonwood chronology (RecTCS and RecTCS+PC1), or omitted (RecPC1).
[b]Regression model constant term (*a*) and coefficients on the first and second predictors (*b*1 and *b*2). Standardized regression coefficients on predictors are given in parentheses.
[c]Adjusted R^2 of regression (R^2_{adj}), increase in R^2_{adj} over using just PC1 of conifer chronologies in simple linear regression (Δ), reduction-of-error statistic from leave-one-out cross-validation (RE), and root-mean-square error computed from cross-validation residuals (RMSE).

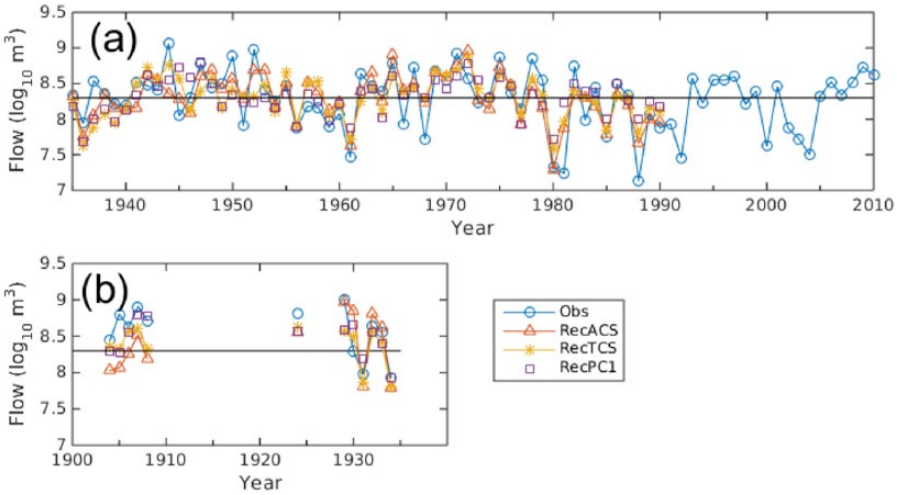

Figure 3. Calibration-period time plots of observed and reconstructed flows of Little Missouri River near Watford City, North Dakota: (a) flows for 1935–1990 calibration period and more recent years and (b) flows before start of calibration period. Observed flows before 1935 have been estimated by regression using data from the gage at Medora, located about 173 km upstream from the gage near Watford City. Horizontal line is at the 1935–1990 mean of log-transformed observed flows. See text for description of chronologies and reconstruction models.

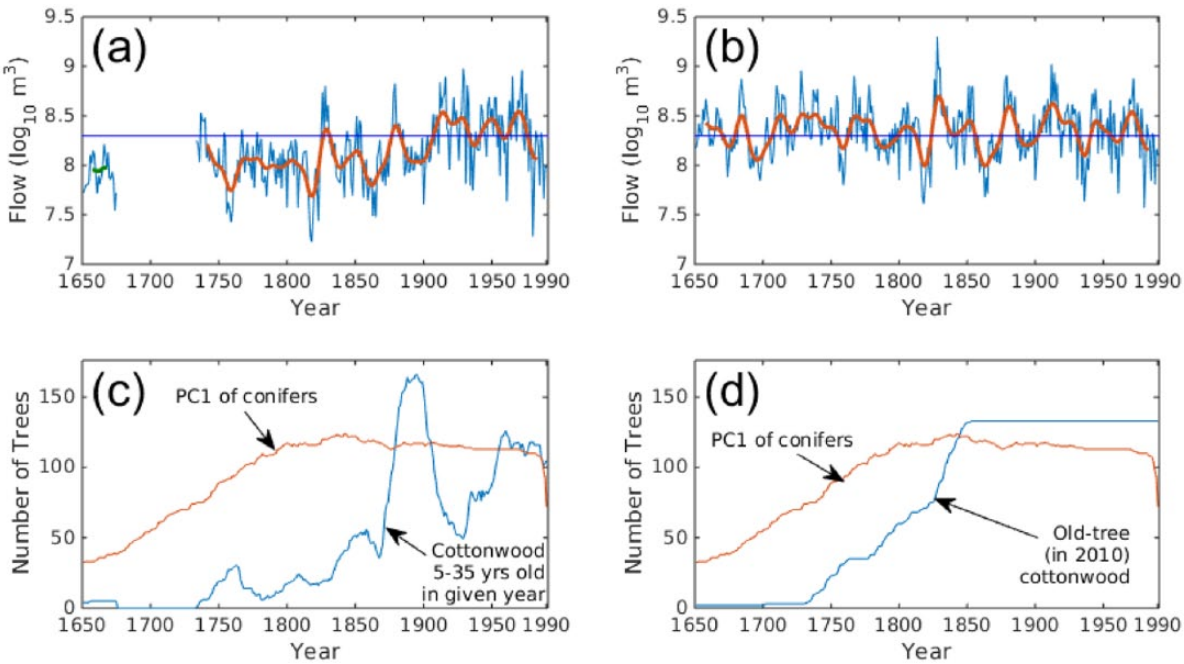

Figure 4. Reconstructions of flow and time plots of sample sizes (number of trees) of contributing tree-ring predictors from regression models with alternative sets of two predictors. (a) RecACS + PC1, reconstruction from young-tree ACS cottonwood chronology and first principal component (PC1) of four spline-detrended conifer chronologies. (b) RecTCS + PC1, reconstruction from spline-detrended chronology of old cottonwood trees and PC1 of four spline-detrended conifer chronologies. (c) Sample size of chronologies contributing to RecACS + PC1. (d) Sample size of chronologies contributing to RecTCS + PC1. Annual data are plotted for period 1651–1990. Smooth line in top two plots is time series smoothed with a 17-weight Gaussian filter (file S8 in the Supplemental Material, available online), whose frequency response is 0.5 at a wavelength of 19 years.

the Souris River Basin in western North Dakota, Saskatchewan, and Manitoba (Vanstone, 2012), and historic records were used to qualitatively reconstruct flows in the Red River, Manitoba, from 1796 to 1870 (Rannie, 1999). The following wet and dry periods in the reconstructed flow record of the LMR have corresponding periods in the temporally overlapping parts of these two other flow reconstructions: low flows in the 1750s, around 1820, late 1830s, early 1860s, late 1880s and 1890s, 1930s, late 1950s; and 1980s, and high flows in the 1730s, 1760s, late 1800s, late 1820s, around 1850, around 1880, 1910s, 1940s and early 1950s, and around 1970.

At the century scale, RecACS+PC1, but not RecTCS+PC1, shows a large sustained increase beginning in the mid-1800s. Statistically, the contrast in the levels of RecACS+PC1 before and after 1900 mirrors a corresponding contrast in the ACS young-tree chronology: cottonwoods in the 5–35 year age range before 1900 grew more slowly than cottonwoods in the same age range after 1900. An upward shift in growth rate of cottonwood is not restricted to just the young trees. An ACS chronology for ring ages 36–165 years shows a similar shift (Figure 5). These are independent pieces of evidence for a shift in growth in the sense that the set of rings of the different age bands are by definition mutually exclusive. The low-frequency

trend represented by the shift was removed by the conventional detrending procedure in the TCS chronology used in RecTCS+PC1. Why the increased growth in cottonwood? It is unclear that this increase can be attributed to increased April–July flow of the LMR. In comparison with flows at the gage near Watford City extended by regression from observed flows at Medora, RecACS+PC1 appears to be consistently too low in 1904–1906, and both RecACS+PC1 and RecTCS+PC1 are low in 1905, 1907, and 1908 (Figure 3b). These discrepancies could result from inaccuracy in the flow reconstructions, from variation in flow between the gages or from problems with estimation of discharge in the earliest years of gage operation.

Table 2. Mean observed and reconstructed flow in transformed and original units[a] for selected time periods.[b]

	Mean flow	
	$Log_{10}(m^3)$	$10^6 m^3$
Observed		
1935–1990	8.2989	294
RecACS+PC1		
1935–1990	8.2989	255
1901–1990	8.3366	279
1840–1900	8.0673	144
RecTCS+PC1		
1935–1990	8.2989	244
1901–1990	8.3541	276
1840–1900	8.2867	241

[a]Regression models for reconstruction were calibrated with log-transformed flows. Column 2 is the arithmetic mean of flows for time period indicated in column 1. Means in column 3 are computed after first back-transforming the log-transformed observed or reconstructed annual (April–July total) flows back to original units of million cubic meters.
[b]1935–1990 is the calibration period for reconstructions RecACS+PC1 and RecTCS+PC1; 1901–1990 and 1840–1900 contrast the high flows of the 20th century with lower flows (by RecACS+PC1) in the 19th century.

Dry conditions in the late 19th century are consistent with some but not all previous studies using proxy data in regions surrounding the LMR. A reconstruction of regional-average annual precipitation from conifer tree-ring widths detrended conservatively with negative exponentials or least-square fit straight lines for a region overlapping the LMR shows much low-frequency variance and a transition from dry conditions in 1825–1875 to wet conditions in 1900–1930 (Stockton and Meko, 1983). The reconstruction of summer and annual flows of the Souris River (Vanstone, 2012) singled out the 19th century for low flows: severe and long-lasting reconstructed droughts from 1841 through 1865 and from the late 1880s through the 1890s (Vanstone, 2012). Records of droughts and wet periods over the past 2000 years from North Dakota lake cores (Mg/Ca ratios in calcite of ostracodes, and salinity inferred from diatoms) do not indicate generally dry conditions throughout the 1800s, but do support a shift from dry to wet from the late 1800s to early 1900s (Figure 2, Fritz et al., 2000). A study of droughts and wet periods in the Red River Basin, southern Manitoba, from ring widths of *Q. macrocarpa* deserves mention here for its use of RCS methods to retain low-frequency information (St George and Nielsen, 2002). That study found a similar sustained increase in ring width beginning in the mid-1800s, attributed it to a release from shade caused by intense logging, and removed it from the chronology by applying two separate age–ring width curves for trees established before and after 1800. Consistent with the hypothesis of a post-logging release, the increase in growth in our ACS chronology was contemporaneous with settlement and logging on the floodplain. Unlike oak, however, plains cottonwood is a disturbance-dependent species whose seedlings become established in open areas away from adult trees, resulting in relatively even-aged stands (Friedman and Lee, 2002). Therefore, removal of old trees has a relatively small effect on light levels experienced by younger trees. Logging would strongly affect light levels in stands aged 5–35 years only if young trees within those stands were cut. Other factors apart from flow that could have contributed to this sustained growth increase include lengthening of the growing season, increased precipitation and temperature without

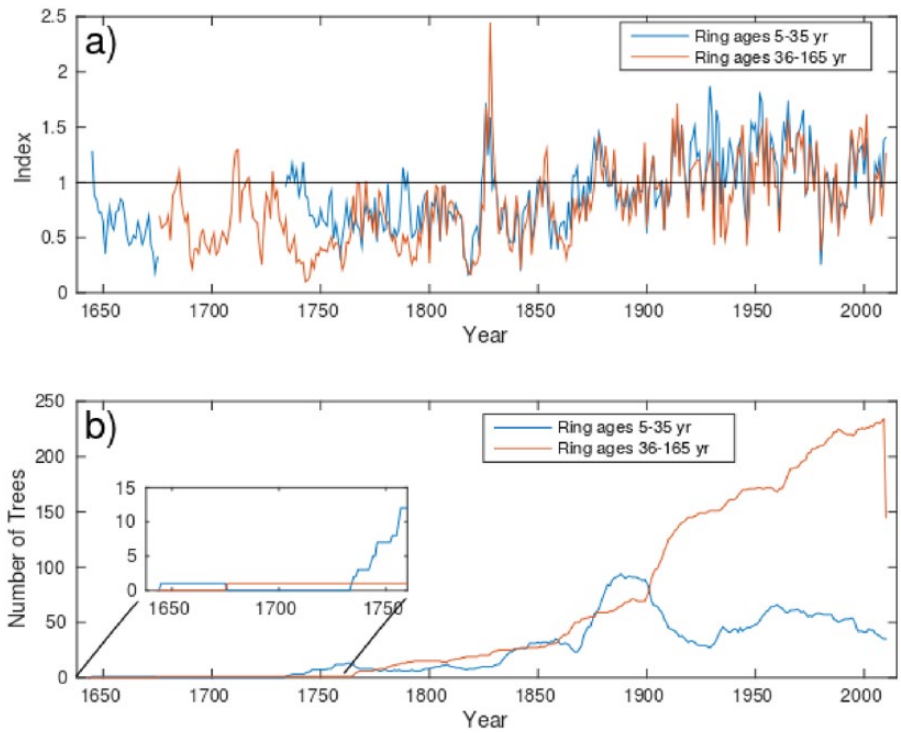

Figure 5. Time plots of (a) site chronologies and (b) sample size for age-curve-standardized versions of cottonwood chronology from two different age bands of rings.

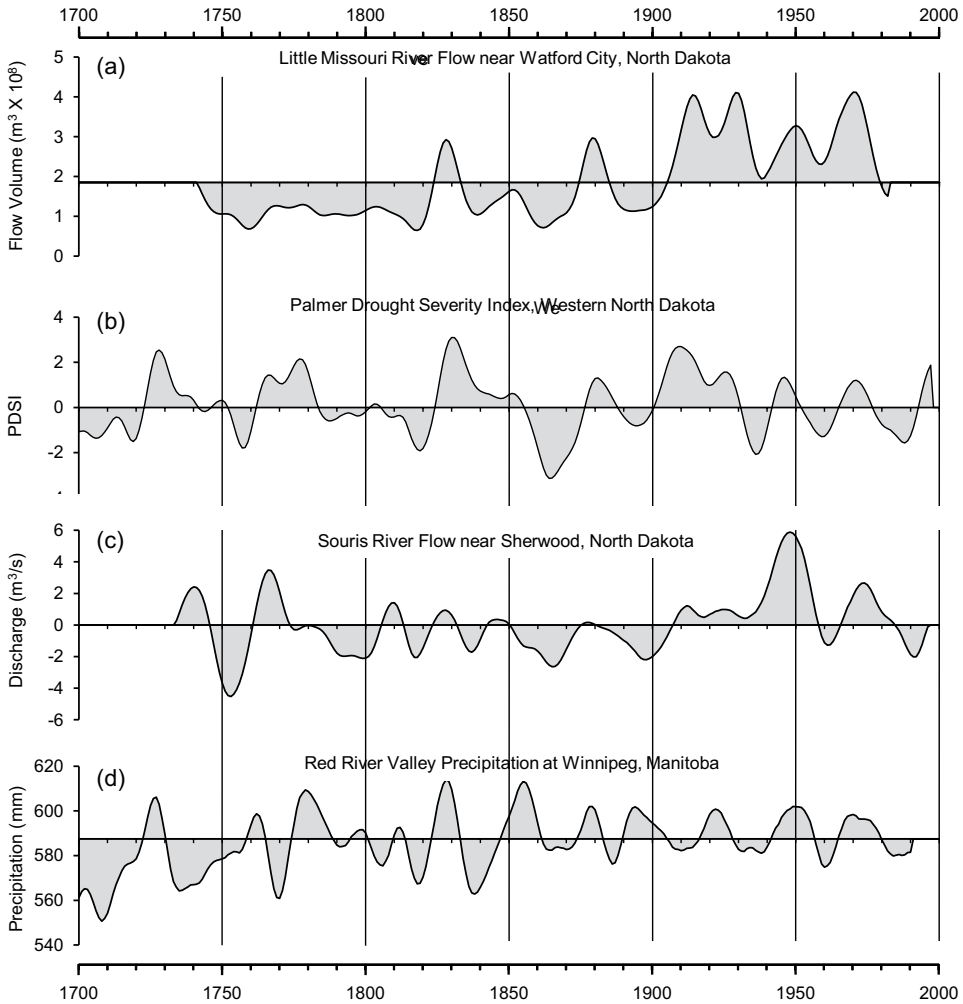

Figure 6. Reconstructions of hydroclimatic change in the northern Great Plains since AD 1700. (a) April–July flow volume of the Little Missouri River near Watford City, North Dakota, RecACS + PC1 (this study); horizontal line is the mean. (b) Summer (June–August) Palmer Drought Severity Index for a grid point at 102.5W 47.5N in western North Dakota (Cook et al., 2008). (c) Mean departures of annual discharge (October–September) of the Souris River near Sherwood, North Dakota, based on chronologies of riparian *Quercus macrocarpa* (Vanstone, 2012). (d) Annual (August–July) precipitation at Winnipeg, Manitoba, based on chronologies of riparian *Q. macrocarpa* in the Red River Valley (St George and Nielsen, 2002); horizontal line is the mean. All series are smoothed by a 17-weight Gaussian filter (file S8 in the Supplemental Material, available online).

corresponding increase in flow, fertilization by nitrogen or carbon dioxide, and channel bed aggradation resulting in a sustained rise in the water table. Replication of our results with data from other sites is necessary to address this issue.

A broader implication (beyond the LMR) of our study is that cottonwood and other riparian tree species are potentially valuable in themselves or in combination with upland tree-ring chronologies to dendrochronological flow reconstruction. That the TCS cottonwood chronology improves the accuracy of flow reconstruction for the LMR (Table 1, Figure 3) underscores the fact that a riparian chronology from perhaps 15–20 old riparian trees standardized by conventional methods (TCS method) can be useful for flow reconstruction. This approach should be generally practical for watersheds in general. In time-nested reconstruction models (e.g. Meko, 1997), riparian chronologies would most likely be helpful in improving the accuracy of the most recent nests or those over the most recent centuries. The abundance of cottonwood along rivers across the interior western United States (Friedman et al., 2005) suggests there may be many other opportunities to apply this approach. Flow reconstruction will be most successful where the relation between ring width and flow is strong and monotonic, as in relatively arid floodplains where growth is strongly limited by water availability and flood duration is relatively short. Ring width will not be as useful for flow reconstruction where growth is not limited by moisture scarcity (Dudek et al., 1998) or where flood duration is long enough to reduce growth by causing reducing conditions in the root zone (Clark, 1987; St George and Nielsen, 2002). One weakness of cottonwood from the point of view of flow reconstruction in low-elevation watersheds like the LMR is the early snowmelt runoff (usually March or April) relative to the growing season, which does not begin until May.

The ACS approach demonstrated here also has broader applications, although the sampling requirements are demanding. One requirement for sound application of the ACS method is that the sample of available riparian trees is diverse enough to allow a reasonably accurate estimate of dependence of ring width on ring age. Factors other than age also affect width, and the goal is a large and representative sample such that when all ring-width series are aligned at pith date and averaged over trees, those other influences, which ideally are not functions of ring age, are smoothed out in averaging. Any correlation of those confusing

factors with ring age will distort the estimated age curve. Because the objective is flow reconstruction, it is especially important that climate, a major determinant of flow, is not correlated with ring age. If just a narrow age band (e.g. 5–35 years) of rings is used in the chronology, accurate estimation of the full age curve becomes less important. However, then, sample size could become problematic because it is important that a large sample of rings of the target age band can be found in all segments of the tree-ring record. A large number of young trees augmented by a small number of older trees would not satisfy the requirements for ACS, as the curve of expected ring width as a function of age would be biased by the climate of the most recent decades. Care should also be taken to provide a reasonably constant number of cores from sampled trees, such that the final ACS chronology is not overly dependent on growth variations of a few trees. Of the 331 trees used in the ACS chronology development in this study, 79% are represented by two cores, 16% by one core, and a few trees by up to five cores. Alternative weighting schemes in chronology development could perhaps mitigate bias because of uneven sampling, but we did not address this issue.

In improving the ACS approach to flow reconstruction from riparian trees, future studies should also address dependence of ring width of same-age trees on hydrologic setting (e.g. distance from channel, soil characteristics).

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