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Time scale effect and uncertainty in reconstruction of paleo-hydrology

Saman Razavi,[1,2,3]* Amin Elshorbagy,[1,2] Howard Wheater[1,2,3] and David Sauchyn[4]

[1] *Global Institute for Water Security, University of Saskatchewan, Saskatoon, Saskatchewan, Canada*
[2] *Department of Civil and Geological Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada*
[3] *School of Environment and Sustainability, University of Saskatchewan, Saskatoon, Saskatchewan, Canada*
[4] *Tree-Ring Lab, Prairie Adaptation Research Collaborative, University of Regina, Regina, Saskatchewan, Canada*

Abstract:

Tree-ring-based reconstructions of paleo-hydrology have proved useful for better understanding the irregularities and extent of past climate changes, and therefore, for more effective water resources management. Despite considerable advances in the field, there still exist challenges that introduce significant uncertainties into paleo-reconstructions. This study outlines these challenges and address them by developing two themes: (1) the effect of temporal scaling on the strength of the relationship between the hydrologic variables, streamflow in this study, and tree growth rates and (2) the reconstruction uncertainty of streamflow due to the dissimilarity or inconsistency in the pool of tree-ring chronologies (predictors in reconstruction) in a basin. Based on the insight gained, a methodology is developed to move beyond *only* relying on the annual hydrology-growth correlations, and to utilize *additional* information embedded in the annual time series at longer time scales (e.g. multi-year to decadal time scales). This methodology also generates an ensemble of streamflow reconstructions to formally account for uncertainty in the pool of chronology sites. The major headwater tributaries of the Saskatchewan River Basin, the main source of surface water in the Canadian Prairie Provinces, are used as the case study. It is shown that the developed methodology explains the variance of streamflows to a larger extent than the conventional approach and better preserves the persistence and variability of streamflows across time scales (Hurst-type behaviour). The resulting ensemble of paleo-hydrologic time series is able to more credibly pinpoint the timing and extent of past dry and wet periods and provides a dynamic range of uncertainty in reconstruction. This range varies with time over the course of the reconstruction period, indicating that the utility of tree-ring chronologies for paleo-reconstruction differs for different time periods over the past several centuries in the history of the region. The proposed ensemble approach provides a credible range of multiple-century-long water availability scenarios that can be used for vulnerability assessment of the existing water infrastructure and improving water resources management. Copyright © 2015 John Wiley & Sons, Ltd.

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INTRODUCTION AND SCOPE

Climate has, throughout history, varied irregularly on a variety of time scales with diverse impacts on hydrology and river flow regimes (Mitchell, 1976; Blöschl and Montanari, 2010). However, the relatively short length of observational records of hydrologic variables limits our ability to understand the medium-term to long-term properties of change and variability in hydrology. An improved understanding of such change and variability is of significance in the context of discussion of future climate change and past climate non-stationarity (Milly *et al*., 2008; Razavi *et al*., 2015), and hence for (1) the evaluation of reliably available water resources, (2) optimal planning and management of existing water resource systems, and (3) cost-effective design and development of new water resources infrastructure. Natural proxy records of hydroclimatic behaviour over the past several centuries or millennia have introduced opportunities to go beyond the limited periods of observational records. There are a variety of sources in nature that embed such long records, including tree rings, sediments in streams, lakes and swamps, ice layers, and fossil pollen profiles (see Loaiciga *et al*., 1993 and references therein). Among these, tree-ring data and their induced reconstructions of paleo-hydrology have become available in many regions in the world; examples include Chile (Urrutia *et al*., 2011), China (Gou *et al*., 2007), Britain (Jones *et al*., 1984), Morocco (Till and Guiot, 1990), the Canadian provinces of Quebec (Boucher *et al*., 2011) and Alberta (Axelson *et al*., 2009; Sauchyn *et al*., 2011), and across the United States (Cleaveland and

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*Correspondence to: Saman Razavi, School of Environment and Sustainability, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.
E-mail: saman.razavi@usask.ca

Stahle, 1989; Cleaveland and Duvick, 1992; Woodhouse and Lukas, 2006; Gray and McCabe, 2010; Maxwell *et al.*, 2011).

Tree-ring data, through the science of dendrohydrology, provide a platform for better understanding the annual to multi-decadal variabilities in climatic and hydrologic variables (Cleaveland and Stahle, 1989; Gou *et al.*, 2007; Sauchyn *et al.*, 2011). Tree rings are superior proxies of paleo-hydrology in comparison with the majority of other natural proxy records, because they are capable of archiving hydro-climatic behaviour at a fine temporal resolution (i.e. yearly and sub-yearly). This capability has led scientists to focus on the reconstruction of paleo-hydrology at annual and shorter time scales. Although there is significant promise and utility in such fine-scale reconstructions, there are multiple challenges in the mapping of tree-ring data onto hydrologic variables (such as streamflows) at these scales. These challenges introduce significant uncertainty, which limits the credibility of, and confidence in, such paleo-hydrology reconstructions. These uncertainties are largely epistemic, and the realistic quantification of their extent is nontrivial. Also, despite the availability of tree-ring data at the annual time scale, the identification of lower-frequency climate signals through tree rings and reducing uncertainty of streamflow reconstruction at all frequency ranges remain significant challenges (Meko *et al.*, 2012; Franke *et al.*, 2013; Ault *et al.*, 2014).

This paper outlines and discusses the main challenges and develops a methodology to address or circumvent some of them. To this end, two main themes are developed as follows:

1. the investigation of the effect of analytical time scale on the relationship between tree-ring chronologies and streamflows. In general, it is hypothesized that this relationship will become stronger for longer time scales and that the improved strength can be of significant value for more credible and reliable reconstruction of paleo-hydrology.
2. the understanding and quantification of uncertainties involved in paleo-reconstructions, particularly the uncertainty due to the dissimilarity or inconsistency between different tree-ring chronologies in a basin (a major source of uncertainty).

Combining the understanding gained under the aforementioned two themes, this study goes beyond the common practice of producing a *single* set of reconstructions for *annual* hydrologic variables. Instead, we propose a methodology that generates an *ensemble* of time series on *multi-year time scales* for hydrologic variables such as streamflows. This ensemble is indicative of the uncertainty associated with historical reconstruction and provides alternative realizations that can be used directly in the assessment of impacts of paleoclimate on current hydrological and water resource systems.

The headwater tributaries of the Saskatchewan River Basin (SaskRB), originating in the Rocky Mountains in Alberta, Canada, are used as the case study. The SaskRB experiences one of the most extreme and variable climates in the world and embodies a set of critical challenges for water security, which are of particular importance to western Canada and relevant globally (Wheater and Gober, 2013; Wheater and Gober, 2015).

The remainder of this paper is organized as follows. The Section on Dendrohydrology and Its Challenges briefly provides the fundamental concepts of dendrohydrology and outlines the main challenges in this context. The Section on Case Study and Data gives an overview of the study area and the utilized tree species and chronology sites across the basin. The Section on Rationale and Method presents the rationale of the two themes of this study and the proposed method, using case study-specific information. The Section on Results and Discussion reports the results on the new method and compares and contrasts multi-year *versus* annual reconstructions of paleo-hydrology. The paper ends with conclusions and future directions in Section on Conclusions and Final Remarks.

DENDROHYDROLOGY AND ITS CHALLENGES

Dendrohydrology is the science of utilizing the properties of dated tree ring widths of moisture-sensitive, long-living trees to investigate and reconstruct the history of hydrologic variables such as river flows (Fritts, 1965; Fritts, 1976; Stockton and Jacoby, 1976). Dendrohydrology requires an understanding of the relationships between hydrologic variables of interest and the biological response of trees to the ambient conditions governed by those hydrologic forcing variables (Loaiciga *et al.*, 1993). The biological response of trees is recorded primarily in the widths of tree rings; however, there are also other measurable indicators such as earlywood and latewood densities that are useful for extracting seasonal patterns (Loaiciga *et al.*, 1993; Boucher *et al.*, 2011). As outlined by Brockway and Bradley (1995), the basic concept of dendrohydrology is that climate variables such as precipitation in year t, which generate streamflows, have influence on the annual growth rate of trees in years t to $t+m$. The 'biological carryover effect' of trees acts as a storage capacity that enables them to maintain their growth for m years following a given year, even under dry future conditions. On the other hand, a relationship might also be established between streamflows in year t and the growth rate of trees in the preceding years t-k to t-1, as the growth rates can represent the contributions of watershed carryover storage, e.g. due to groundwater and snowpack resources, to the streamflows. As such, the general form of models for the reconstruction of annual streamflow time series can be written as follows:

$$y_t = f(\boldsymbol{x}_{t-k}, \ldots, \boldsymbol{x}_{t-1}, \boldsymbol{x}_t, \boldsymbol{x}_{t+1}, \ldots, \boldsymbol{x}_{t+m}) \quad (1)$$

where y_t is the annual streamflow in year t, $\boldsymbol{x}_t = \{x_{i,t}|i = 1, \ldots, n\}$ is a vector of n tree-ring index chronologies (i.e. allowing for multiple data sources), and $f(.)$ is typically an empirical, data-driven function used for the mapping. An 'index chronology' is defined as the average of the 'detrended' growth rates (tree-ring widths) of several sampled trees located within a 'chronology site'. In the remainder of this paper, the terms 'index chronology' and 'growth rate' are used interchangeably. Detrending is intended to remove age-dependent biological growth trends in the tree-ring width series. The description of different detrending methods in dendrohydrology can be found in Fritts (1976) and Cook and Briffa (1990). The time series of the standard index chronology of the chronology site i, $x_{i,t}$ for $t = 1, \ldots, T$, where T is total number of years, possesses a mean value of about unity (for sufficiently long time series), which corresponds to the normal growth rate. Principal component analysis is also commonly applied in this context to eliminate the cross-correlations between the index chronologies and extract their dominant components to be used as the predictors in Equation 1 (Hidalgo *et al.*, 2000).

There are five main challenges and issues in the reconstruction of paleo-hydrology on the basis of tree-ring chronologies, as outlined in the following:

1. Tree-ring widths and streamflows are just two of the *many* interrelated factors involved in the underlying complex cause-and-effect system. As such, they are only capable of explaining a portion of the variance and behaviour of each other.

The predictive ability of reconstruction models is typically assessed by the percentage of the portion of the variance of streamflows in the period of observational record that can be explained by the reconstruction models (100% for a perfect model). This percentage can be quantified by the coefficient of determination, R^2. Depending on the geographical location, available tree species, tree-ring data availability, and the type of the reconstruction model used, a range of reconstruction performance has been reported in the literature. Examples of model performance for annual streamflow reconstruction include 37% and 43% in Axelson *et al.* (2009), 42% in Urrutia *et al.* (2011), 49% in Gou *et al.* (2007), 57% in Cleaveland and Stahle (1989), and 63–76% in Woodhouse and Lukas (2006). The unexplained portion of the variance may be deemed to be the contribution of other factors involved in the underlying system.

The underestimation of the variance may also be in part due to the application of squared-errors-based metrics in fitting reconstruction models (see Gupta *et al.* (2009) for the decomposition of such metrics) and also the poor ability of index chronologies to represent peak flows, because of the biological limit of the response of tree growth to high precipitation and low evapotranspiration during wet years (Fritts, 1976; Sauchyn *et al.*, 2011). The resulting 'compressed variance' of streamflow reconstructions limits the confidence of dendrohydrologists in interpreting the magnitude of extreme paleo-climate. Bias correction techniques, which are commonly used in the context of climate change projections (Piani *et al.*, 2010; Ehret *et al.*, 2012), may be used to artificially re-scale the variance or modify the distribution of reconstructions. The work of Cook *et al.* (2004) is an example of the use of bias correction for paleo-reconstruction.

There are a variety of statistical function approximation techniques that can be potentially used for developing the mapping function f in Equation 1. However, multiple linear regression is the most commonly used technique in this context (Gangopadhyay *et al.*, 2009), as it appears to be a simple, but effective, approach to model the direct, monotonic (approximately linear) physiological relationship between the available moisture and tree growth rate. One problem is that, even with such a simple technique for reconstruction, different datasets and ways to process tree ring data can result in substantial differences in the reconstructed paleo-streamflows in a given region (Hidalgo *et al.*, 2000; Prairie *et al.*, 2008; Gangopadhyay *et al.*, 2009).

2. The short-term persistence (autocorrelation) in the time series of standard index chronologies is typically significantly higher than that of observed streamflows.

The elevated persistence in growth time series is a major artefact because of the biological carryover effect of trees. Accurate representation of the short-term persistence in the reconstructed streamflow time series is very important, as the persistence of wet and dry years has significant implications for the management of water resources. One way to address this issue is to utilize autoregressive (AR) filters to artificially remove the extra persistence and align the autocorrelation structure of the time series of standard index chronologies with the one of the streamflow records (Meko *et al.*, 2001). It is also common to fully remove the autocorrelation structure of a standard index chronology, by fitting an AR-type model (e.g. an autoregressive moving average model) to the entire time series and calculating the residuals; the resulting residual time series is called a 'residual index chronology' and can be directly used as a predictor in reconstruction (Cook, 1985). Although residual index chronologies do not possess any noticeable autocorrelation when the autocorrelation is calculated over their full-length period, in their sub-periods (e.g. multi-decade long), there may still exist some significant, positive or negative, autocorrelation structure. More importantly, AR-type models are capable of modelling not only short-term persistence in time series but also, to a large extent, their long-term variabilities. Therefore, there is a significant risk that residual index chronologies may be emptied of such very important information available in the associated standard index chronologies. This will be the focus of a follow-up paper.

3. The *assumption of stationarity* in the hydrology-growth relationship across centuries is in question.

The relationship between tree-ring widths and hydrologic variables may be changing with time. However, this relationship and the resulting mapping models are typically assumed stationary over time – a reconstruction model calibrated on the period of observational record is assumed valid and accurate for the preceding centuries. Exploring possible non-stationarities in this relationship is non-trivial, because of the limited length of the periods of observational record. Generating an ensemble of models (with different parameters and predictors), which ensures covering a wide range of possible input–output relationships, might circumvent this limitation. Such possible non-stationarity certainty adds to the uncertainty in paleo-reconstructions.

4. The process of the reconstruction of paleo-hydrology typically involves *extrapolating* beyond the range of streamflows in the observational record.

Reconstruction models, as they are calibrated to the period of observational record, perform best as long as the statistical properties of the set of index chronologies over time remain consistently within the ranges experienced in the calibration period. This is despite the fact that standard index chronologies, and therefore hydrologic conditions, in a region can be significantly non-stationary over time (Razavi *et al.*, 2015). As such, the resulting reconstructions can go beyond the range on which the reconstruction model was conditioned. This imposes limits on the inferences based on paleo-reconstructions for extremely dry or wet periods. This challenge has been well-discussed in the literature (e.g. Graumlich and Brubaker, 1986; Meko, 1997). Evidently, care must be particularly taken when interpreting the magnitude of reconstructed paleo-events that are beyond the range of observational records. Such interpretations may be more challenging for inferred extremely wet periods, as tree-ring widths frequently underestimate wet conditions. When extrapolation is involved, linear models may be deemed the most reliable models for reconstruction.

5. Appropriate detrending of tree-ring width records is critically important, as low-frequency trends in tree-ring width time series due to long-term climate variations may not be easily distinguishable from age-dependant biological and other growth trends.

There are multiple plausible approaches towards detrending the time series of tree-ring widths. Given the fact that the functional forms of these approaches are different, the resulting time series of standard index chronologies differ from one approach to another. Such differences may be significant, particularly for long records. There have been efforts to characterize and address this challenge (Cook and Peters, 1981; Cook *et al.*, 1995). The extent of this difference (and the resulting uncertainty) for a given case study, however, may be evaluated by generating an ensemble time series of standard index chronologies of the same tree-ring site through the different detrending approaches. Razavi *et al.* (2015) propose a graphical approach for the examination of regional consistencies of index chronologies over time in an attempt to identify the chronologies whose low-order frequency trends are regionally inconsistent.

CASE STUDY AND DATA

The SaskRB with an area of 406 000 km^2 covers parts of the Canadian provinces of Alberta, Saskatchewan, and Manitoba and the American state of Montana. SaskRB is a Regional Hydroclimate Project of the World Climate Research Programme's Global Energy and Water Exchanges. A map of the SaskRB with its major tributaries located in Alberta is shown in Figure 1. Most of the water in this basin (80–90%) originates from the Rocky Mountains in Alberta, while a large portion of the basin on the prairies almost never contributes runoff to the main streams (Pomeroy *et al.*, 2005; Martz *et al.*, 2007). Reliable evaluation and management of water resources in this large basin are critically important, as this basin is a pivotal agricultural region in Canada. In addition, there are other significant competing water demands across the basin including municipal, hydropower, industrial, and environmental uses.

The analysis of proxy records and the reconstruction of paleo-streamflows in the major tributaries of the SaskRB, the North Saskatchewan, Red Deer, Bow, and Oldman Rivers are of interest in this study, as they are the main source of surface water in the SaskRB. A set of

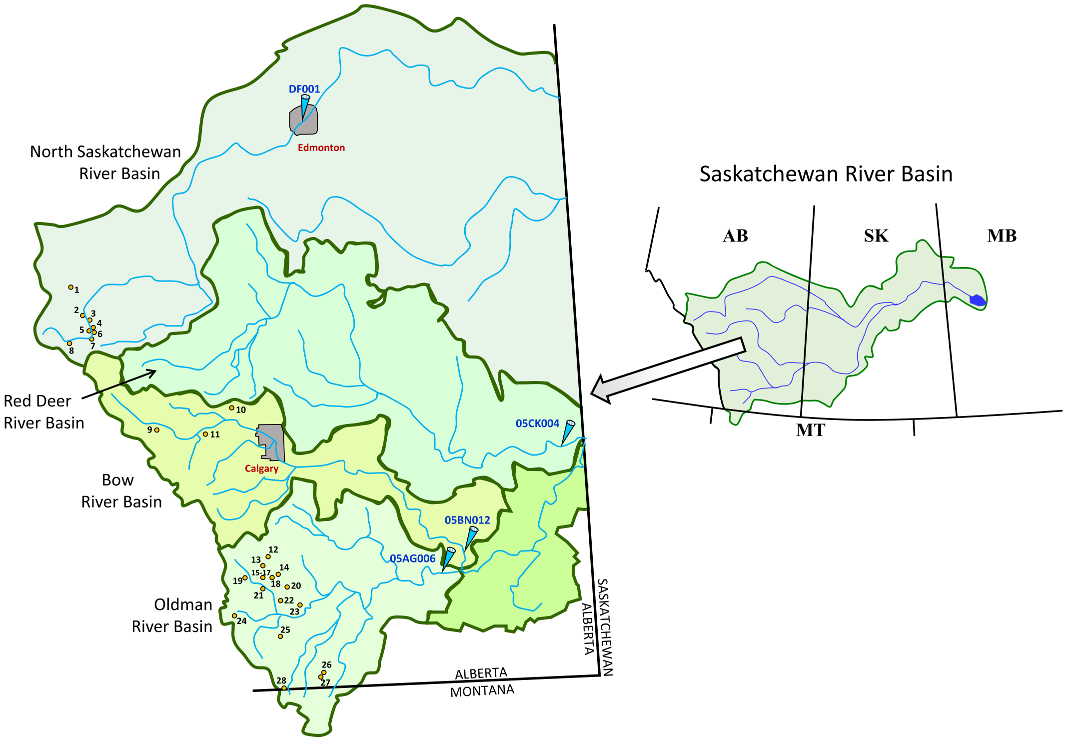

Figure 1. Map of the tributaries of the Saskatchewan River Basin and the locations of the chronology sites (circles) and streamflow gauges (cones)

naturalized flow time series for the historical period of 1912–2001 at the four gauging stations shown in Figure 1 is used in the analysis. The naturalized flows at each gauge have been generated by Alberta Environment and Sustainable Resource Development and represent the flow regime in the basin as if there were no human interventions. There is a relatively rich source of tree-ring data available across the headwater areas of SaskRB (http://www.parc.ca/urtreelab/). A set of 28 tree-ring chronologies, listed in Table I and shown in Figure 1, is used here. The North Saskatchewan and Oldman Rivers contain the majority of the chronology sites, whereas, in the Red Deer sub-basin, appropriate long-living, moisture-sensitive trees have not been identified and sampled yet. The length of tree-ring records varies significantly at different chronology sites. The longest records available in the North Saskatchewan and Oldman sub-basins date back to 1000s and 1300s, respectively, while the shortest record used begins at 1800 AD. There have been efforts to reconstruct the annual streamflows for different tributaries of the SaskRB (Case and MacDonald, 2003; Axelson *et al.*, 2009; Sauchyn *et al.*, 2011). Further, Fleming and Sauchyn (2013) analysed the previously reconstructed streamflow time series of two major tributaries of the SaskRB to study the shifts and variance in water availability.

Most of the tree ring chronologies used are from low elevations and dry sites, south and west-facing slopes with thin soils. The sites were chosen for the lack of availability of soil moisture except during snowmelt or after a rain. Tree rings were measured within 0.001 mm from high-resolution (12001 dpi) images of polished wood samples using WinDendro Density, a semiautomated image analysis system designed for tree rings. The measured tree ring series were standardized using the program ARSTAN (Cook, 1985). To remove the juvenile biological growth trends in the tree ring series, conservative detrending by a negative exponential curve was used. The standardized ring-width series were averaged for each site, using a mean value function that minimizes the effects of outliers. The resulting time series of the standard chronologies (without any prewhitening) were used in this study. A full description of the methods used for building the chronologies is available in Axelson *et al.* (2009) and Sauchyn *et al.* (2011).

RATIONALE AND METHOD

Effect of time scale

Tree-ring-based reconstruction of paleo-hydrology has been mainly based on the correlations between annual (or sub-annual) data of chronologies and hydrologic variables. Figure 2 shows the correlation coefficients between the annual (water year – October to September) naturalized streamflows in the SaskRB and the standard

Table I. List of chronology sites and their tree species, associated river basins, and data availability – PG for *Picea glauca*, PM for *Pseudotsuga menziesii*, and PF for *Pinus flexilis*

River basin	No.	Chronology site	Tree species	Data available dated back to year
North Saskatchewan	1	BSG	PG	1730
	2	DEA	PM	1520
	3	WIP	PF	1750
	4	WRC	PM	1620
	5	TWO	PM	1540
	6	SFR	PF	1038
	7	WPP	PF	1110
	8	SKC	PF	1680
Bow	9	JOLA	PM	1446
	10	WCH	PM	1390
	11	SIP	PM	1740
Oldman	12	WCK	PM	1750
	13	CAL	PM	1640
	14	BMN	PF	1580
	15	LBC	PM	1610
	16	OMR	PM	1370
	17	BDC	PM	1550
	18	OMRw	PF	1640
	19	WSC	PM	1570
	20	DCK	PM	1660
	21	BCK	PM	1660
	22	CAB	PM	1440
	23	HEM	PF	1510
	24	ELK	PF	1540
	25	BVL	PM + PF	1730
	26	LEC	PM	1758
	27	BZR	PF	1570
	28	BND	PM	1800

index chronologies (annual growth rates) over the historical period. As can be seen, there is a range of correlation coefficients from negligible to significant between the annual streamflows and index chronologies at different sites – the highest correlation coefficient is 0.62, which is calculated between flows in the Bow River and the JOLA chronology site.

The idea in this paper is to move beyond *only* relying on the annual hydrology-growth correlations and to utilize *additional* information embedded in the annual time series at longer time scales (multi-year to decadal time scales). Hydrologic/growth time series demonstrate different rates and patterns of variability at different time scales. Understanding the similarities and differences of the time series of the two at different time scales is expected to help us improve the credibility of paleo-hydrology reconstructions. We will explain how incorporating the information at longer time scales has potential to address challenges 1 and 2 outlined in Section on Dendrohydrology and Its Challenges.

Hydrology-growth correlations across time scales. To illustrate the effect of time scale, Figure 3 shows the flow time series of the Oldman River over the historical period along with the chronology time series of the CAB tree-ring site (over the same period) on an annual basis as well as their 3-year, 5-year, 10-year, and 30-year moving averages. As can be seen, an increase in the moving window length (smoothing) leads to an increase in the similarity of the resulting moving average time series of the flows and growth rates. This indicates that, for longer time scales, the CAB chronology can more accurately explain the variance of the Oldman River flows (at those longer time scales). We note that possible lags on the annual scale in causal effects may be eliminated/reduced on longer time scales. Figure 4a–e shows the scatter plots of the time series of flows *versus* the growth rates in Figure 3a–e. On the annual scale, the CAB chronology can only explain 28% of the variance of the flows; whereas on the 3-year time scale, the growth rate becomes capable of explaining 50% of the 3-year flow variance. This figure becomes 60%, 65%, and 86% for the time scales of 5, 10, and 30 years, respectively.

The scaling effect as explained previously, through which the strength of the correlations monotonically improves for longer time scales, is not always observed. Figure 5 shows the correlation coefficients between the growth rates and flows in the Oldman River on five time scales ranging from annual to 30 years. In the vast majority of the chronologies, the correlation coefficients improve when moving from the annual time scale to the

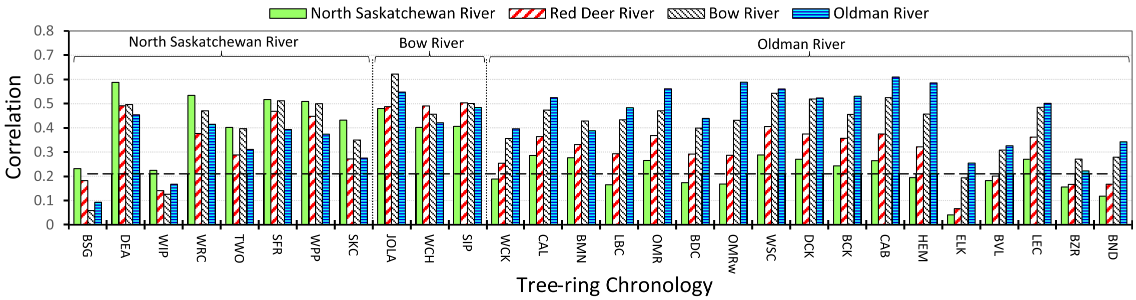

Figure 2. Linear correlation coefficients between the standard index chronologies and the water year flows in North Saskatchewan, Red Deer, Bow, and Oldman Rivers – the dashed line represents 5% two-tailed significance level

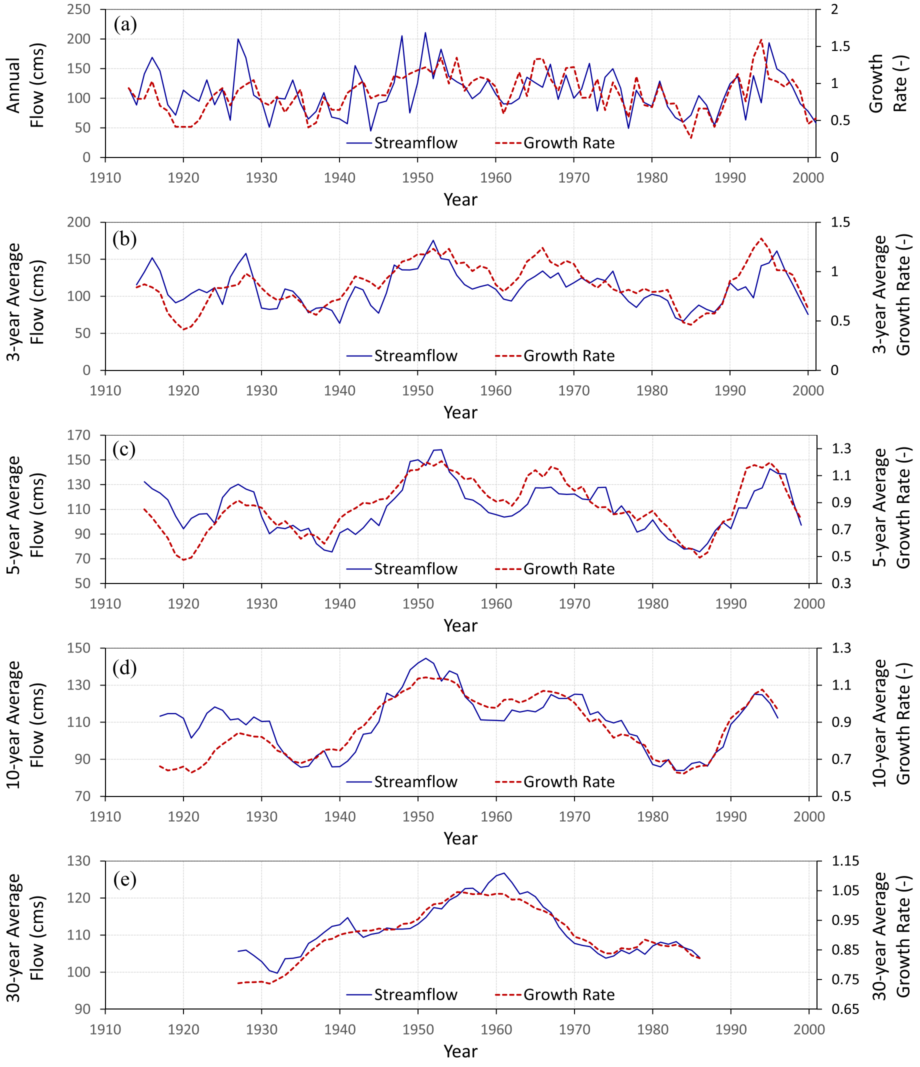

Figure 3. Time series of flows in the Oldman River along with the time series of growth rates in the CAL chronology – (a) annual, (b) 3-year, (c) 5-year, (d) 10-year, and (e) 30-year moving average time series

3-year and 5-year time scales. However, there are cases where the correlations degrade for longer time scales; for example, see the BMN chronology in Figure 5.

The investigation of the effect of time scale on the relationship between tree-ring chronologies and hydrologic variables on the historical period is an effective way to evaluate the suitability of available chronologies for the reconstruction of paleo-hydrology. Such an approach can also be useful in identifying subsets of chronologies that may be preferable for capturing multi-decadal (as opposed to interannual) flow variations. In general, we can put more confidence in the reconstructions that more accurately represent the hydrology observed in the historical period. Therefore, the direct use of the stronger relationships on multi-year time scales will result in reconstruction models that can explain the variance of hydrologic variables at those time scales to a larger extent and produce more credible reconstructions of paleo-hydrology.

Autocorrelation structure, Hurst-type behaviour, and variability across time scales. Figure 6 shows the autocorrelation function of the annual flow time series in the Oldman River along with those of annual growth time series over the historical period for the chronologies located in the Oldman basin. Evidently, there is significant short-term persistence (memory) in the annual tree growth, compared with that of annual flows, lasting for a couple of years. Such elevated persistence will be transferred to any resulting reconstruction that is based on annual hydrology-growth correlations. On longer time scales, however, the persistence properties of the flows and tree growth rates are more consistent, as demonstrated in the following.

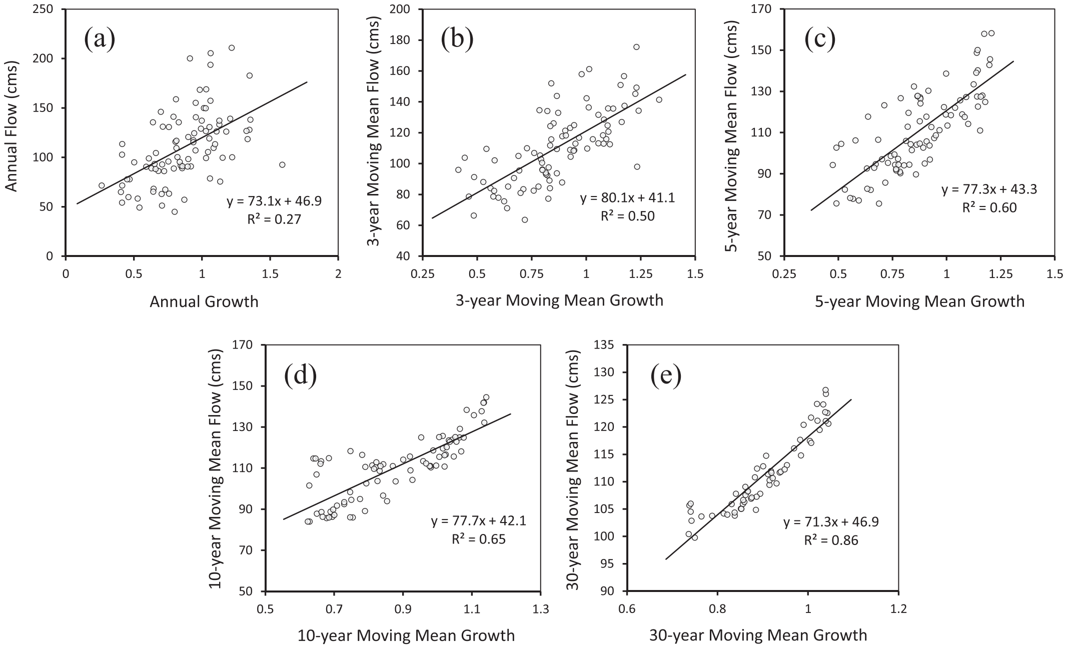

Figure 4. Scatter plots of the flows in the Oldman River *versus* the growth rates in the CAL chronology on different time scales – plot (a) is on annual time scale; plots (b–e) are on 3-year, 5-year, 10-year, and 30-year moving mean data, respectively

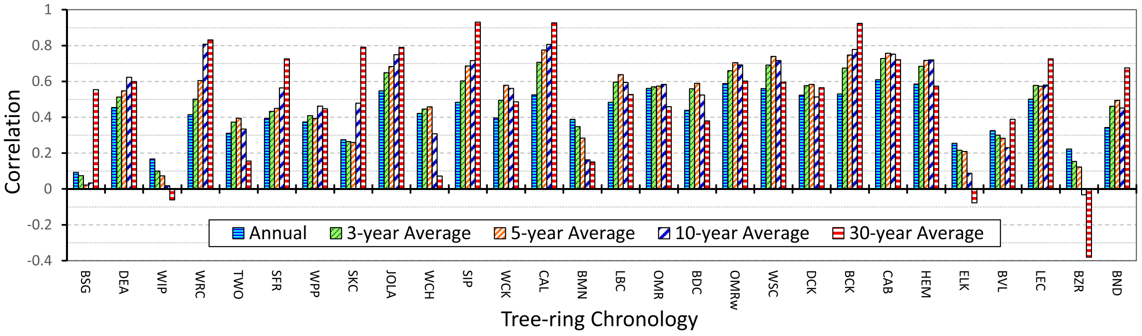

Figure 5. The effect of time scale on the strength of the correlation between the tree growth and flow in Oldman River

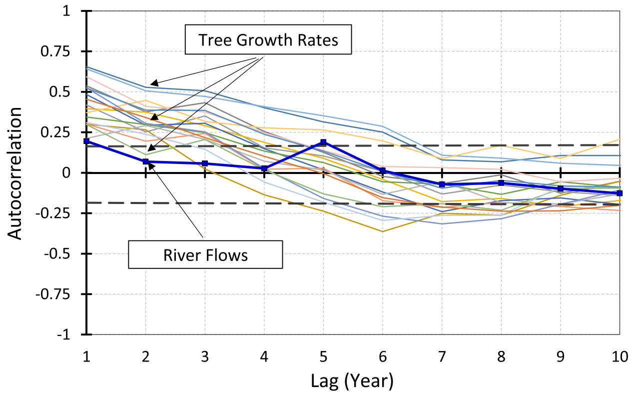

Figure 6. Autocorrelation functions of annual (water year) river flows in the Oldman River and annual growth rates for the historical period at all the chronologies located in the Oldman basin – the dashed lines represent 95% confidence limits

Figure 7 plots the *variance* of the time series of flows and growth rates in the Oldman basin during the historical period *versus time scale*, on the log–log scale. The variance at the different time scales was calculated using multi-year time scale time series derived from the annual time series by a 'segmenting and averaging' procedure (see Section on The New Reconstruction Method). As expected, the variance decreases as the time scale increases for all the time series, however, the slope of the linear function that fits the points on the log–log scale (rate of decrease) can be different from one time series to another. This herein called 'variance *versus* time scale' plot (and the associated slope) is an effective characterization of *variability of the time series across time scales*. The slope is typically benchmarked against the slope of a random process (also shown on the plot), which possesses

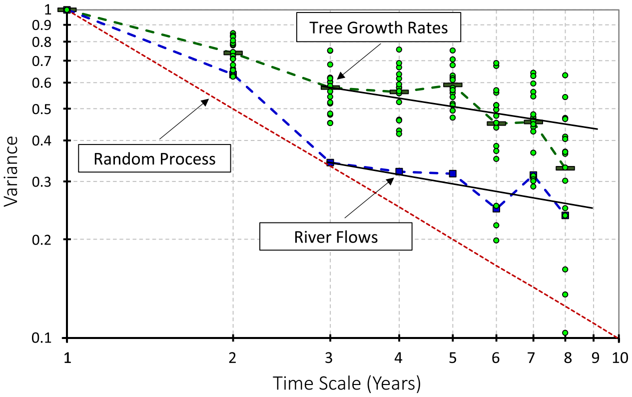

Figure 7. Variance-versus-time-scale plot for flows in the Oldman River (square markers) and growth rates (circle markers) on the historical period at all the chronologies located in the Oldman basin – note that all the annual time series are standardized so that all the time series have an identical variance of unity at the annual scale; the solid lines are fitted on the data of the time scale of 3 years and longer

no short-term or long-term persistence. *The difference from the random process is attributable to the persistence (at a range of time scales) in the time series*. For the purpose of this plot, all the original time series are standardized so that their variances on the annual scale are identical (=1). For short time scales (shorter than 3 years), the slope of the two (flows and growth rates) is considerably different, with the slope associated with flows closer to that of the random process. This is an alternative representation of what has been already shown in Figure 6, which indicates the existence of larger short-term persistence in growth rates compared with flows. However, for long time scales (longer than 3 years), the slopes of the two are similar. This similarity in slopes indicates that the time series of flows and growth rates are very similar in their long-term variability behaviours.

The variance *versus* time scale plot is a means to study the ‘Hurst Phenomenon’, which indicates the existence of long-term persistence in hydrologic time series (Hurst, 1951; Klemeš, 1974; Salas *et al.*, 1979; Mudelsee, 2007). The slope of the line passing through the points on the plot is known to be 2H-2, where H is called the ‘Hurst exponent’ (see Beran, 1994, page 92). H is 0.5 for random (uncorrelated) processes, is greater than 0.5 for processes with positive persistence, and is less than 0.5 for processes with negative persistence. Note that the Hurst Phenomenon is typically discussed when a long time series of a process is available, as it becomes evident on large time scales. In this case, however, we are limited to the short period of observational record (89 years), which only allows the investigation of the variability on time scales equal or shorter than 8 years – the number of data values on the 8-year time scale obtained by segmenting and averaging is 10. The important message, nevertheless, is that, the variabilities of the hydrologic and growth time series on time scales greater than ~3 years are consistent in this example. Although only one example is not conclusive, it raises the importance of characterizing the variability in the time series across time scales and reproducing it in the reconstructions of hydrologic variables. Correct understanding and representation of long-term persistence in paleo-hydrologic time series is of significance (Fleming, 2014). The state-of-the-art reconstruction approaches, however, which are based on annual (or sub-annual) correlations, do not recognize such significance.

Uncertainty due to the choice of predictors

The classically defined sources of prediction uncertainty in hydrologic modelling, including parameter, structural, and data uncertainties, can also be defined in the reconstruction of paleo-hydrology. Prediction (i.e. reconstruction) uncertainty in this context, however, has been generally evaluated through prediction intervals generated by regression. In regression analysis, predictors (i.e. chronologies) and the form of the regression model are specified *a priori*, and the resulting prediction intervals are only due to the uncertain model parameters (i.e. regression coefficients).

The choice of predictors can introduce significant uncertainty that, in essence, augments the other sources of uncertainty in modelling and prediction listed previously. This is because reconstruction models can be sensitive to their predictor pool (e.g. Woodhouse *et al.*, 2006). In this study, we address this source of uncertainty, referred to as the ‘uncertainty due to the choice of predictors’ hereafter. The problem is that during calibration of a reconstruction model (e.g. regression fitting), different subsets of available chronologies may fit observed hydrologic variables comparably well, whereas, their resulting paleo-reconstructions may be significantly dissimilar. Such different paleo-reconstructions may be deemed equally credible though. Therefore, there is a need to characterize this uncertainty, as it produces an *envelope* of possible scenarios of the water availability of a region before the beginning of historical records.

The new reconstruction method

The proposed approach in this paper is to directly reconstruct multi-year hydrologic time series based on hydrology-growth correlations at the respective time scale. First, a procedure is required to derive multi-year time scale time series from annual hydrology and growth time series. Segmenting and averaging is the most direct way to change the scale of the annual time series to the time scale of interest. For example, to derive a time series on the 10-year time scale from an annual time series with a length of 80 years, the annual time series should be divided into eight 10-year-long, non-overlapping segments, and the time series on the 10-year time scale is obtained by averaging the elements of every individual segment. This procedure, however, results in time series with a very limited number of data points (only eight data points in this example), and therefore, has limited utility in case of typically short periods of observational record. Moving average time series can to-some-extent circumvent this limitation (71 data points, albeit correlated, in a 10-year moving average time series for the aforementioned example) while effectively representing the correlation information on the time scale of interest required for mapping and reconstructions.

To directly reconstruct multi-year moving average flows, we revise the reconstruction model formulated in Equation 1 as follows. The input to the reconstruction model for each chronology site i, where $i = 1, \ldots, n$, becomes $\frac{1}{k+m+1}\sum\left(x_{i,t-k} + \ldots + x_{i,\ t-1} + x_{i,t} + x_{i,t+1} + \ldots + x_{i,t+m}\right)$, and the target output of interest is $\frac{1}{k+m+1}\sum(y_{t-k} + \ldots + y_{t-1} + y_t + y_{t+1} + \ldots + y_{t+m})$. This formulation utilizes the typically higher correlations at multi-year time scales while enabling the reconstruction model to directly transfer the long-term variabilities of the chronologies into the paleo-reconstructions, regardless of the inconsistencies in their short-term persistence. Note that moving averages are perhaps the simplest means to be used with the new method. Using more sophisticated low-pass filters within this method may further improve the quality of reconstruction (not explored here). A multiple linear regression model fitted by the method of least squares is used for mapping and reconstruction. In our analysis (Section on Results and Discussion), we arbitrarily choose $m = k = 2$, resulting in the reconstruction of 5-year moving average streamflows. The residual time series resulting from this reconstruction formulation (regardless of the type of function approximation technique used) may possess significant autocorrelation. Depending on the function approximation technique used (e.g. linear regression), such autocorrelation may violate some of the underlying assumptions and bias some resulting statistical inference, for example, on regression prediction intervals. However, regression coefficients will remain unbiased (best fit) when obtained by the method of least squares.

To quantify the uncertainty in reconstruction due to the choice of predictors, our approach is to develop a range of possible models with different input sets for characterizing the underlying processes, instead of searching for one optimal model (like Parasuraman and Elshorbagy (2008)). To this end, a pool of potential predictors of paleo-hydrology (chronology sites) is defined for the reconstruction of paleo-streamflows in each river, based on their proximity and availability. All possible combinations of predictors are tested, resulting in 2^m-1 reconstruction models, where m is the number of chronology sites in the pool. All these reconstruction models are evaluated and ranked based on the Akaike Information Criterion (AIC) (Hipel and McLeod, 1994). The AIC rewards goodness of fit, which always improves (or remains the same) by adding more predictors, while penalizing larger numbers of model parameters, thereby discouraging over-fitting. The cross-validation strategy is also used to test the performance of each model. The ensemble of acceptable reconstruction models provides an envelope of paleo-streamflows that represents a range of possibilities that might have occurred in the past.

Note that although annual extremes may be hidden in the reconstructed multi-year time series of paleo-streamflows, they can be reproduced via a hybrid approach. Multi-year time scale reconstructions can be disaggregated to the annual scale on the basis of the standard chronologies (or residual chronologies with adjusted short-term persistence), which are defined on the annual scale. A methodology can be developed to (1) utilize longer time-scale relationships to reconstruct longer-term hydrologic variability (i.e. magnitude and extent of cycles and trend) and (2) use annual-scale variability in the growth rates to reconstruct the annual hydrologic variability to be assembled on longer time scale paleo-reconstructions.

RESULTS AND DISCUSSION

Multi-year reconstructions

The 5-year moving average flows in the North Saskatchewan, Red Deer, Bow, and Oldman Rivers were reconstructed for the period 1600 to 1912. Reconstruction (multiple linear regression) models were developed to map the 5-year moving average index chronologies as the predictors to the target moving-average river flows. These models were calibrated and evaluated using the observational data and then used for the reconstruction of the pre-observational period.

There are 14 chronology sites across the tributaries of SaskRB with data available from 1600, which formed the set of predictors. Four and eight of these sites are located within the North Saskatchewan and Oldman River basins, respectively, and only two in the Bow River basin. For the reconstruction in the North Saskatchewan and Oldman Rivers, only the chronology sites located within their respective basins were used, resulting in a total of 15 (2^4-1) and 255 (2^8–1) potential combination sets of predictors.

In the case of the Red Deer and Bow Rivers, because of the lack of chronology sites in their basins, we included all the 14 chronology sites across the SaskRB in the pool of potential predictors. However, only the 1- to 2-combinations of 14 sites were evaluated as potential sets of predictors for these rivers, resulting in 105 sets $(14+\binom{14}{2})$. In the reconstruction experiments of both the Red Deer and Bow Rivers, larger sets of predictors were also evaluated (the results are not reported). Although with larger sets of predictors, reconstruction models with improved R^2 and AIC for these two rivers were attainable, the resulting variance of the reconstructed flows for the observational period (through cross-validation) was significantly larger than the variance of the observations. Such inflation in variance, which propagates to the entire paleo-reconstructions, may invalidate the associated reconstruction model.

The best 11 and 14 reconstruction models, in terms of AIC, were selected for presentation and uncertainty quantification for the North Saskatchewan and the Oldman River, respectively. The numbers of selected models (acceptable AIC threshold) were rather subjective and based on visual inspection of the reconstructions. In the case of the North Saskatchewan River, the pool of the best 11 sets consists of models with 1 to 4 predictors with R^2 values ranging from 0.56 to 0.67. For the Oldman River, the best 14 models have 4 to 7 predictors with R^2 values ranging from 0.70 to 0.72. For each of the Red Deer and Bow Rivers, the ten best reconstruction models were selected, all of which have two predictors. The selected reconstruction models of the Red Deer River have R^2 values of 0.54 to 0.69 and for the Bow River have R^2 values of 0.64 to 0.73.

Figure 8 shows the time series of reconstructed 5-year moving average flows in the North Saskatchewan, Red Deer, Bow, and Oldman Rivers for the period 1600 to 2001. The envelope created by the set of time series in each river represents the uncertainty due to the choice of predictors. This uncertainty is variable with time, and for certain periods, is larger than that of others. For example, in the case of the Oldman River, shown in Figure 8d, the reconstructions for period 1875–1910 demonstrate relatively large uncertainties, whereas, for period 1760–1785, the uncertainties seem to be minimal. The accuracy of the predicted flows in the observational period through cross-validation is an indication of the accuracy of the paleo-reconstructions.

The reconstruction performance in the Red Deer River is the poorest, perhaps because of the absence of tree ring chronologies in the basin. It is interesting that for the Red Deer River, the 'best model' departs significantly from the rest of the ensemble. The results overall demonstrate

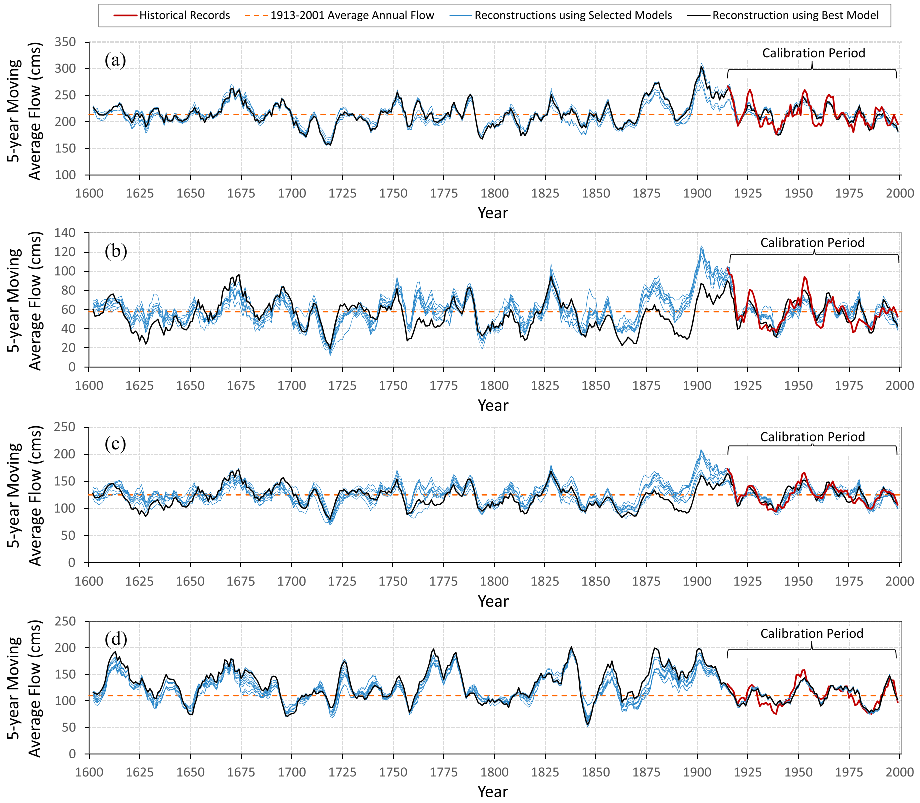

Figure 8. Time series of reconstructed 5-year moving average flows in (a) North Saskatchewan, (b) Red Deer, (c) Bow, and (d) Oldman Rivers. The best model is the model with minimum Akaike information criterion. The shown reconstructed flows for the calibration period are the results of cross-validation

that the ‘best model’ alone may not provide a complete picture of paleo-hydrology from a water resources management point of view and confirm the need for ensemble reconstruction of paleo-hydrology.

Annual reconstructions versus longer-scale reconstructions

In the previous sections, we showed that the relationships between the streamflows and growth rates are typically stronger on longer time scales. The stronger relationships presumably result in paleo-streamflow reconstructions that are more defensible and more representative of the properties of streamflows in the past. However, given the possibility to directly reconstruct annual streamflows, which may seem more appealing and useful from a water resources point of view, one may question the utility of longer-time-scale reconstructions. In this section, we compare and contrast the annual-year-scale against five-year-scale reconstructions in the Oldman River basin, which is the richest in terms of the number of chronology sites.

Figure 9 shows an ensemble of 14 annual time series of paleo-streamflows reconstructed through the same method and data used for the 5-year moving average reconstructions of Figure 8d. The best regression R^2 value obtained was 0.49 for a model with six predictors and the lowest R^2 values among the 14 models was 0.45 for a model with four predictors. As expected, the fitting capability and explained variance of the linear regression model on the data in the calibration period is higher for 5-year time scale compared with annual scale.

To conduct a more direct comparison, we smoothed the annual reconstructions via 5-year moving averaging (called ‘annual-based 5-year reconstructions’) and plotted, in Figure 10, the range (minimum and maximum) of the resulting 5-year moving average time series along with the range already obtained in Section on Multi-year Reconstructions, by directly reconstructing 5-year moving averages. As can be seen, the reconstruction ranges obtained by the two approaches are quite different for certain periods of time. The differences are particularly significant for wet periods, when annual-based 5-year reconstructions are consistently lower than 5-year time scale reconstructions. Given that the tree-ring widths frequently underestimate wet conditions on the annual basis, these results demonstrate the superiority of the longer-scale reconstructions for wet conditions. The underestimation of annual extreme wet conditions by tree rings can be due to the biological limit of the response of tree growth to high precipitation during wet years (Fritts, 1976; Sauchyn *et al.*, 2011). The reconstructions of the two approaches for dry periods are generally consistent and somewhat similar – with the exception of the dry periods around 1700 and 1845 when the direct 5-year scale reconstructions indicate more dryness compared with those of the annual-based reconstructions.

The variance of the annual-based 5-year reconstructions is significantly smaller than that of the 5-year scale reconstruction. However, the autocorrelation in the residual time series of annual-based 5-year reconstructions is comparable with that of residual time series of direct 5-year reconstructions. The former for the Oldman River varies between 0.81 to 0.85 across the 14 reconstructions, while the latter varies between 0.76 and 0.78. Obviously, such autocorrelation is significant and should be taken into account, if further statistical inference through regression analysis is desired.

As shown, the analytical time scale in the reconstruction of paleo-hydrology has a significant impact on the final products. In the absence of other sources of data for paleo-hydrology, it is non-trivial to validate/invalidate any of these products. However, given that the longer time-scale reconstructions are capable of better preserving and representing the statistical properties observed in the historical period, their products are deemed more reliable and advisable.

Although annual extremes may be hidden in the reconstructed multi-year time series of paleo-streamflows, they can be reproduced via a hybrid approach. Multi-year time-scale reconstructions can be disaggregated to the annual scale on the basis of the standard chronologies (or residual chronologies with adjusted short-term persistence), which are defined on the annual scale. A methodology can be developed to (1) utilize longer time-scale relationships to reconstruct longer-term hydrologic variability (i.e. magnitude and extent of

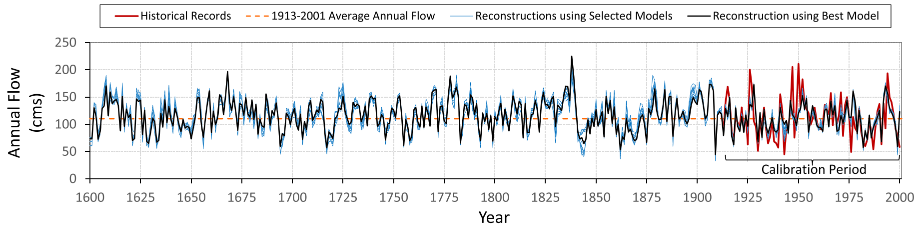

Figure 9. Reconstructed time series of annual flows in the Oldman River. The best model is the model with minimum Akaike information criterion. The shown reconstructed flows for the calibration period are the results of cross-validation

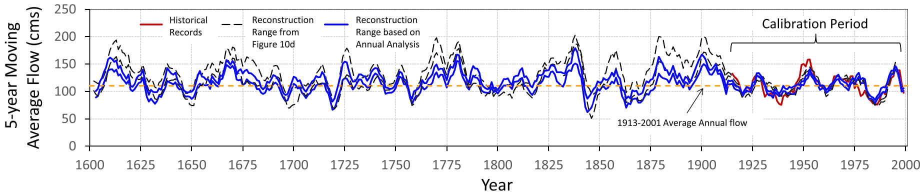

Figure 10. Comparison of the range of reconstructions obtained in Figure 8d with the range of the 5-year moving average time series derived from annual reconstructions of Figure 9

cycles and trend) and (2) use annual-scale variability in the growth rates to reconstruct the annual hydrologic variability to be assembled on longer time scale paleo-reconstructions.

CONCLUSIONS AND FINAL REMARKS

Temporal scaling has a significant impact on the strength of the correlations between tree growth rates and hydrologic variables in a region. Departing from the annual resolution to multi-year or decadal resolution typically leads to an improvement in the credibility of paleo-hydrology reconstructions. The following points outline the findings and conclusions in this regard:

- Multi-year reconstructions better represent the hydrologic variability (variance) and better capture the lower-frequency trends.
- Multi-year reconstructions better preserve the persistence properties (particularly the Hurst-type behaviour) of hydrologic time series.
- The quality of chronology data (strength of embedded signals) may differ at different time scales. Some chronologies may be more suitable for longer-scale reconstructions and vice versa. Therefore, the best chronologies as predictors of climate/hydrology in a region may be different at different time scales.
- Improvements in multi-year reconstructions may *not* be at the expense of losing information on annual variability and extremes. Methods can be developed to disaggregate longer time-scale reconstructions guided by annual growth variability represented by the chronologies possessing strong signals of annual variability in hydrology. The development of such hybrid methods can be a potential direction for future research.

There is a great deal of uncertainty in the reconstruction of paleo-hydrology, arising from different sources. The quantification of uncertainty due to the choice of the best predictors was of particular interest in this study. An approach was developed to generate an ensemble of reconstructions based on different credible sets of predictors (chronologies). This approach provides an envelope of credible possibilities of what might have happened in the hydrology of a region. We found that

- the uncertainty due to the choice of predictors is typically variable in time, and the extent of uncertainty at different periods in the past can be different,
- this uncertainty is in part a representation of inconsistencies between chronologies across a region in the paleo-period, and
- further investments for the identification and collection of more moisture-sensitive trees are needed. With more chronologies in a region, the inferred uncertainty due to the choice of predictors may be increased; this uncertainty, however, approaches the ‘true’ uncertainty when the conventional mapping method is used for reconstruction (as also used in this study).

We conclude with that our method addresses challenges 1, 2, and 3 (of the five challenges outlined in Section on Dendrohydrology and Its Challenges) to different extents, by increasing the explained variance, better preserving persistence, and generating an ensemble of reconstructions that heuristically captures a range of possibilities in the presence of non-stationarities in the hydrology-growth relationship. Finally, we note that our method provides not only improved reconstruction power but also the basis for ensemble simulation of water resources systems, which can be accomplished via forcing water allocation and management models by the many multiple-century-long historical water availability scenarios reconstructed through the ensemble approach to quantify dynamic uncertainty. Hence, we suggest that this method and its resulting reconstructions have significant potential utility in hydrological and water resources analyses.

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