We are extremely grateful for the constructive interactive reviews of our paper entitled: "Paleo-hydrologic reconstruction of 400 years of past flows at a weekly time step for major rivers of Western Canada". The comments were constructive and helped immensely in improving the paper. The format of this author response is to address each reviewer comment sequentially by first quoting the comment and then providing a response immediately below.

Review 1:

Question 1

"*Why should we make sure that the reconstructed flows "properly preserve the statistical properties of the reference flows, particularly, short- to long-term persistence and the structure of variability across time scales", mentioned later in the abstract and used in the methodology*"

This is an important comment, and the paper has been changed to make this point clearer (Page 16, lines 4-7). This point has been mainly ignored in the previous work, as discussed in Razavi et al. (2016) and Razavi and Vogel (2018). The reconstructed flows over 'the reference period' were constructed in a way to preserve the statistical properties of 'the reference flows'. This is to ensure that the important statistical properties in the entire reconstructed flow dataset are sufficiently representative. The outcome of any modelling study that uses these flows will depend to a large extent on the presence of these statistical properties. Many performance measures for example in a water management modelling study will depend on the variability of weekly flow or the long-term autocorrelation in the flow.

Question 2

"*Similar to Razavi et al. (2016), only the four …" needs to be explained more in-depth in this manuscript to make it self-contained.*"

The reviewer makes a good point by this comment relating to the MLR models for the North Saskatchewan River and the Oldman River sub-basins using the four and eight chronology sites falling within the sub-basins, respectively. It was expected that the MLR models would have less uncertainty if they were constructed using the chronology sites falling within the respective basins. Unfortunately, the Red Deer River and Bow River sub-basins contain few or no chronology sites, so as a way around this, all the chronology sites were used in the construction of their MLR models. As evident in the results shown in Figure 3, the use of chronology sites falling within a particular sub-basin to construct the MLR model for that sub-basin does in fact increase the accuracy of the reconstructed biennial flows. This point has been made clearer in the manuscript (Pg 5 lines 20-25).

Question 3

"*Adding to comment 2 above, the following methods/approaches need to be explained in Section 2 to make the manuscript self-contained: a. Page 5: why MLR is expected to reconstruct flow from tree ring data, adequately. b. Page 5: The "leave-one-out cross-validation strategy" c. Page 6: The "random matching*".

The reviewer brings up very good points by these comments, and addressing them in our paper should improve the description of the methodology considerably. Multiple linear regression (MLR) is a simple but effective method of modelling the direct monotonic (approximately linear) relationship between tree growth rate and flow. Since both flow and tree ring growth depend on soil moisture, we can expect a fairly linear relationship. This has been stated in the paper on Page 5 lines 15-20. The "leave-one-out-cross-validation-strategy" maximises the validation of the MLR models given that the overlap period between the tree-ring chronologies and reference flows is relatively short. Here, if the overlap period is n years, n-1 validations are possible by sequentially calibrating using n-1 years of data and validating against the year left out, with the average R^2 of the n-1 validations used in the final analysis of the model performance. This type of validation can also help identify and avoid overfitting. A short explanation has been included on Page 5, lines 28 – 30. Random matching relates to step four in Figure 2, where as the reconstructed biennial flows are stepped through, a reference average biennial flow with similar hydrological properties is randomly selected. The randomness of the selection allows an ensemble approach to be adopted as multiple datasets can be generated that are different but retain the same underlying statistical properties. This has been stated on Page 6, line 20

Comment 4

"*Authors need to elaborate on the negative regression coefficients in table 1. Are they physically meaningful? Could the regression be constrained to take only non-negative coefficients? In the same table, variables (e.g. WWP and JOLA) have to be introduced*."

This is a very good point. The tree growth (as represented by three ring width) and water availability (as represented by streamflows here) are always positivity correlated in moisture-limited settings (not necessarily true in energy-limited settings). This means that a regression coefficient in a single linear regression should always be positive. However, in multiple linear regression, the signs of some of the coefficients might become negative because of collinearity, which relates to the dependence of the tree-ring chronologies. One way to avoid seeing negative signs is to apply principal component analysis (PCA) to the repressors before doing regression. However, applying PCA would not improve the predictive power of the regression in this case, and therefore, has not been conducted. This point has been included in the manuscript (Page 15 lines 8-16). The variables within the MLP models such as 'WWP' and 'JOLA' are codes for tree-ring chronology sites, and we have included a citation where these codes are defined (Page 9 in Table 1).

Comment 5

"*Page 7: What do author mean by naturally in "The biennial reconstructed time series naturally demonstrate smaller variability compared with the biennial flows in the reference period, when MLR models are used for reconstruction."*

The reviewer has highlighted the use of a term which may cause confusion, and the paper has been adapted to remove the use of the word "naturally". The MLR models fitted by the Least Square Method always produce smaller variance compared with the variance of observations. As such, reconstructed flows will have less variability compared to the reference flows as the tree-ring chronologies will not explain all the variation in the reference flow. The word "Naturally" has been replaced with "As expected" and this point has been explained in the paper (Bottom of page 7).

Comment 6

"*The two year instrumental periods briefly introduced in the abstract need to be explained more in-depth in Section 2. 7*."

The reference to a ”two-year instrumental period” relates to matching the broad properties of the biennial reconstructed flow with those of the biennial average reference flow. In this study, these properties were the hydrological category of wet, average or dry and whether the wetter year in the biennial average occurred in the first or second year. The paper has been adapted to make this point clearer (Page 6 line 8).

Comment 7

“*The persistence calculation should be explained in Section 2*.”

We appreciate the reviewer drawing attention to the need for further explanation. Further description of the autocorrelation calculation has been added to Section 2 (Page 8 line 21-25).

Reviewer 2

Comment 1

“*The authors use R2 to select the best MLR model. Did they consider possible over-parameterization and multicollinearity? Analyzing the standard errors and metrics such as information criteria (e.g. AIC) can identify the optimal models more reliably*.”

We first would like to thank the reviewer very much for his/her time and the constructive comments. The selection of the number of regressors are based on a former study with the same data (Razavi et al. 2016) where Akaike Information Criterion was used. This limited the risk of over-parametrization and over-fitting. Of course, there is always some level of collinearity among the tree ring chronologies. We note that we also applied principal component analysis (PCA) to the tree-ring chronologies and compared the results of MLR with and without PCA (this comparison is not reported), but didn’t find any noticeable difference. This point has been made in the paper (Page 16, lines 9-13).

Comment 2

“*It is mentioned that “weekly flow distribution of the selected reference flow period can be used to construct the weekly flows”. By doing so, the variability in the reconstructed flow will be similar to the reference flow variability, correct? Please discuss how/if this assumption can undermine the estimated variability of reconstructed flows? How does it account for possible recent trends due to the anthropogenic climate change effects*?”

The reviewer brings up an important point with this comment. Given the nature of annual tree growth rings, the intra-year variability of flows cannot be determined from tree-ring reconstructed flows. It is assumed that the reconstructed weekly flows will contain the long-term inter-year variability of flows as represented in the tree-ring data, but intra-year variability will be based on the variability of the reference flow, scaled to the biennial reconstructed flow. From a water resources modelling perspective, this longer-term variability is arguably more important to represent than intra-year variability; for example, it would be persistent long-term droughts that challenge the robustness of water resource systems. This point has been included in the paper (Page 17, lines 19-26)

Comment 3

"*The study focuses on matching the variation and persistence between the observed flow in the reference period and the reconstructed flow. I wonder whether historical/ recent physical processes could have distorted this similarity? For example, recent climate change trends are much stronger compared to the historical periods (prior to the reference period)*"

The reviewer's comment here highlights an important potential confounding factor in the analysis. Indeed, with increasing snow melt under a warming climate, the underlying statistical properties of flow in a water tower-driven catchment such as the Saskatchewan River basin may indeed change considerably compared to the pre-reference period. However, since the reference period used ended in 2000, which is now almost 20 years ago, we must assume that the more recent climate change trends were absent or at least much weaker prior to the turn of the century. The paper has been adapted to highlight this important point (Page 18, last paragraph).

Comment 4

"*P5/L8: I suggest discussing briefly the cause(s) for persistence in tree-ring chronologies and based on that justify why the multi-year approach will overcome the problem. Related to this, how about the role of teleconnection signals, which can affect the records over multiple years*."

The persistence in the tree-ring chronologies is a mixture of the persistence in the climate signal and the biological carry-over effects of trees. The latter refers to the fact that, for example, trees can tolerate water shortage in a dry year and grow well if the preceding year was wet. This effect diminishes for a longer time scale. The study of Razavi et al. (2016) has showed this.

The teleconnection signals typically occur in concert with precipitation in the region, and thus with water availability for tree growth. Therefore, tree-ring chronologies and their respective streamflow reconstructions should carry the teleconnection signals. We have included some discussion of these points in the paper (Page 5, lines 10-15).

.

Comment 5

"*P6/L15-16- It matches the first moment (i.e. the mean). How about higher moments like the variance?*"

The reviewer is referring to this sentence specifically: "The weekly distribution of flows in the selected biennial reference flow period is then used to construct the weekly flow reconstruction scaled to have the same biennial average as the original reconstructed biennial flow." The reviewer brings up an important point with this comment. As shown in Fig. 5 and Fig. 6, the disaggregation approach used was successful in replicating the variance in the reference flow within the reconstructed flow. The variance of the weekly reconstructed flow was in fact assessed during the study to be similar to that of the reference flow. The paper has been adapted to make this finding more explicit (Page 6 lines 26-28).

Comment 6

"*Figure 2, step 3- I wonder how much the yearly average is affected by seasonal variations? i.e. it is possible that larger flow values have the highest influence?"*

The reviewer makes an important point with this comment. At this point in the disaggregation, a relationship between the reconstructed flows and reference flows at a biennial scale is being made. Therefore, the seasonal variation at this point is not considered. We note that three rings provide no meaningful information on sub-annual variability. However, the influence of these much larger flows can be carried into the reconstructed weekly flows during step 4 in Figure 2. This point has been made in the paper (Page 16, second-last paragraph)

Comment 7 onwards: "Technical corrections"

"*P2/L22- Please clarify the "effects of past climate change" as the anthropogenic effects are mainly observed after the 20th century. Related to this, the next line indicates "high long-term variability" of reconstructions, which should be mainly representative of internal variability*".

Earth has always experienced strong climate change effects in the past unrelated to anthropogenic effects. Of course these effects have been intensified in the Anthropocene. Please refer to for example to Cohn and Lins (2005) and Razavi et al. (2015). The document has been adapted to include this point (Page 2, lines 23-25)

Cohn, T. A., & Lins, H. F. (2005). Nature's style: Naturally trendy. Geophysical research letters, 32(23).

Comment 8

"*P2/L32: Please remove "that must be confronted*"

We thank the reviewer for this comment. We have adapted the paper as requested.

Comment 9
"*P3/L2: Use either "streamflow" or "stream flow" throughout the paper*."

The paper has now been corrected in this regard.

Comment 10

"*P3/L2: Is an R2 value of 0.76 low considering that it is based on an indirect estimate of streamflow*?"

We thank the reviewer for bringing up this point. The sentence has been adapted to reflect mostly lower R2 values but some relatively strong relationships.

Comment 11

"*P3/L23: What does "many uncertainties" imply? Large uncertainties or many sources of uncertainties? If the latter, please provide a few others and add references*."

We implied the latter, and the manuscript will be adapted to include examples and citations.

Comment 12
"*P5/L20: What are the chronology predictors?"*

These refer to tree-ring stations used in the MLR models. The paper was adapted to make this clearer (Page 5, line 29).

Comment 13

"*P6/L9-10- Statement is not clear"*

We will ensure that this statement is re-written for improved clarity (Page 6, lines 19-23).

Comment 14

"*P7/L6-7- I suggest rephrasing this statement for example "...smaller variability compared to...because of ...""*

We appreciate the reviewer's suggestion and the paper will be corrected in this regard.

Comment 15

"*P8/L7- the frequency of what?*"

The reviewer highlights an error on our part. Since this is a flow duration curve and nota frequency curve, we should refer to duration and not frequency. We will correct this error in the paper.

Comment 16

"*P8/L12- I think qstd should be in the denominator and qmean in the nominator*"

We will double check whether this equation is written correctly in the manuscript.

Comment 17

"*Table 1- Please spell out the predictors before or after the table. How was the predictor selection performed? and how did the authors consider multicollinearity?*"

The predictors are codes for tree-ring chronology sites. We have provided a citation where these codes are defined. The selection of the number of regressors was based on a former study with the same data (Razavi et al. 2016) that used the Akaike Information Criterion, thereby limiting the risk of over-parametrization and over-fitting. We also applied PCA to the tree-ring chronologies and compared the results of MLR with and without PCA, but didn't find any noticeable difference.

Comment 18

"*P15/L4- In the introduction, it is mentioned that one of the challenges of current approaches is the low R2 values (0.37–0.76). It implied that this issue was addressed in the study, however current results are within this range. Please clarify*"

We thank the reviewer for highlighting this point. While the biennial reconstructions resulted in higher R2 than annual reconstructions for this region, our study did not merely aim to improve the regression fits within MLR models describing the relationships between tree-ring chronologies and naturalised flow. Rather, the paper introduces a method that firstly constructs these relationships between tree-ring chronologies and naturalised flow in a way that preserves persistence properties and variability of hydrological time series. Further, the study introduces a novel method of disaggregating biennial reconstructed flow to weekly flows. The uncertainty, firstly in the relationships between tree-ring chronologies and naturalised flow, and secondly within the disaggregation technique, is addressed through an ensemble approach, by producing a range of viable MLR models for individual catchments and multiple plausible flow time series within the disaggregation. The paper has been adapted to make this point clearer (Page 16, lines 7-14).

Paleo-hydrologic reconstruction of 400 years of past flows at a weekly time step for major rivers of Western Canada

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Abstract. The assumption of stationarity in water resources no longer holds, particularly within the context of future climate change. Plausible scenarios of flows that fluctuate outside the envelope of variability of the gauging data are required to assess the robustness of water resources systems to future conditions. This study presents a novel method of generating weekly-time-step flows based on tree--ring chronology data. Specifically, this method addresses two long-standing challenges with paleo-reconstruction: (1) the typically limited predictive power of tree--ring data at the annual and sub-annual scale, and (2) the inflated short-term persistence in tree--ring time series and improper use of prewhitening. Unlike the conventional approach, this method establishes relationships between tree--ring chronologies and naturalised flow at a biennial scale to preserve persistence properties and variability of hydrological time series. Biennial flow reconstructions are further disaggregated to weekly, according to the weekly flow distribution of reference two-year instrumental periods, identified as periods with broadly similar tree--ring properties to that of every two-year paleo-period. The Saskatchewan River Basin (SaskRB), a major river in Western Canada, is selected as a study area, and weekly flows in its four major tributaries are extended back to the year 1600. The study shows that the reconstructed flows properly preserve the statistical properties of the reference flows, particularly, short- to long-term persistence and the structure of variability across time scales. An ensemble approach is presented to represent the uncertainty inherent in the statistical relationships and disaggregation method. The ensemble of reconstructed weekly flows are publically available for download from https://doi.org/10.20383/101.0139 (Slaughter & Razavi, 2019).

1 Introduction

Water management has traditionally assumed that variability in streamflow fluctuates within a boundary represented by the limited amount of observed data provided by gauging stations. This limited variability has been used to evaluate and manage risks to water management systems. However, it is becoming increasingly clear that the assumption of stationarity can no longer be taken for granted (Milly et al., 2008), particularly within the context of future climate change.

An opportunity exists to derive a paleo-hydrological record that will contain the effects of past climate change. Earth has always experienced strong climate change effects in the past, even in the absence of unrelated to anthropogenic effects.. Of course, these effects have been intensified in the Anthropocene -. Please refer to for example to Cohn and Lins (2005) and Razavi et al. (2015). Reconstructions of flow from tree--ring records for various parts of the world have shown relatively high long-term variability in hydrologic conditions at the multi-decadal to multi-century temporal scale (Agafonov et al., 2016; Axelson et al. 2009; Boucher et al. 2011; Brigode et al., 2016; Case & MacDonald 2003; Cook et al., 2004; Ferrero et al., 2015; Gangopadhyay et al., 2009; Lara et al., 2015; Maxwell et al., 2011; Mokria et al., 2018; Razavi et al. 2015, 2016; Sauchyn et al. 2011; Urrutia et al., 2011; Woodborne et al., 2015; Woodhouse & Lukus, 2006; Woodhouse et al., 2006). Therefore, tree--ring records could provide an opportunity to evaluate water resources systems against a wider envelope of hydrological variability than what is represented in the gauged records. This is critical for improving the resilience of water resources systems to future conditions.

However, there are various challenges associated with the use of tree-~~-~~ring ~~-~~data to reconstruct streamflows~~ that must be confronted~~, as outlined by Razavi et al. (2016) and Elshorbagy (2016), that add to the uncertainty of flow reconstructions, the most important being: 1) tree-ring widths can only explain a portion of the variance in observed streamflow, and past studies correlating ~~tree-ring~~tree-ring chronologies to stream~~-~~flow have obtained relatively low R^2 values, with values as low as ~~in the range of~~ 0.37 but some values as high as ~~–~~0.76 (Razavi et al., 2016) and; 2) there is short-term persistence in ~~tree-ring~~tree-ring chronologies that is typically higher than that in observed streamflow. Prewhitening techniques are commonly used to remove short-term persistence within chronology datasets. However, Razavi & Vogel (2018) found that prewhitening can distort and reduce the structure of variability across time scales. A viable strategy of reducing the disparities in persistence between ~~tree-ring~~tree-ring chronologies and flow while at the same time increasing their correlative strength is to establish the statistical relationships at longer time scales of two to three years (Razavi et al., 2016; Razavi & Vogel, 2018).

Because water resources models require flow input data at daily to monthly time steps, and flow reconstructions from ~~tree-ring~~tree-ring data are typically at a yearly time step, some method of flow disaggregation is required. Although many studies have established relationships between ~~tree-ring~~tree-ring chronologies and flow at~~on~~ the annual scale, very few published studies have attempted to further disaggregate reconstructed flow. Sauchyn and Ilich (2017) estimated 900 years of weekly flows for the North Saskatchewan at Edmonton and for the South Saskatchewan at Medicine Hat. They determined the statistical relationships between ~~tree-ring~~tree-ring chronologies and mean annual naturalised flow using standard dendrohydrological techniques, but further disaggregated yearly flows to weekly using stochastic downscaling while constraining the resulting weekly flows by the statistical properties of the historical record.

Th~~e~~is ~~present~~ study presents ~~appropriate~~ a novel approach~~es and tools~~ for reconstructing flows from ~~tree-ring~~tree-ring data and disaggregating these flows~~it~~~~yearly flows~~ to weekly while taking into account reconstruction uncertainty through an ensemble approach. As a result, ~~F~~four hundred years of weekly flows were generated for the four major sub-basins of the Saskatchewan River Basin. The Saskatchewan River is~~,~~ a river of great ecological, social and economic importance in Western Canada. The approach of reconstructing flow from ~~tree-ring~~tree-ring chronologies contains multiple sources~~a large number of~~~~many~~ uncertaint~~i~~yes, including the choice of predictor chronologies and the choice of disaggregation technique (Razavi et al., 2016). The present study presents an ensemble approach ~~of~~ for encompassing these uncertainties.

2 Case study, data and methodology

2.1 Case study

The Saskatchewan River Basin (SaskRB) ~~(SaskRB; ~400,000 km²)~~ in Western Canada is a large river basin with an area of approximately 400,000 km^2 that transcends the Alberta, Saskatchewan and Manitoba provinces, and also extends into a small part of the American State of Montana (Fig. 1). The east-facing Rocky Mountains to the west at over 3,000 m in elevation act as the ‘water tower’ of the basin (Martz et al., 2007; Pomeroy et al., 2005), contributing up to 95% of the total basin flow, after which the elevation of the basin drops to 750 m, 450 m and 300 m on the plains of Alberta, Saskatchewan and Manitoba, respectively, transitioning from alpine forest to prairie grasslands and river valley forest. Long sunny winters and short hot summers characterise the climate of the basin, and there is a dramatic rainfall gradient from west to east, with precipitation of up to 1,500 mm year^{-1} in the mountains to 300 mm year^{-1}–500 mm year^{-1} on the semi-arid plains.

2.2 Data

Tree-ringTree-ring data for the major headwater tributaries of the SaskRB were used, namely the North Saskatchewan, Red Deer, Bow and Oldman rivers. Naturalised flows generated by Alberta Environment and Sustainable Resource Development for four gauging stations (1912–2001) representing each of the four headwater tributaries were used in the analysis (see Fig. 1). A total of 16 tree-ringtree-ring chronology sites were used, with most from sites chosen for soil moisture availability only during snowmelt or rainfall. These chronology data were obtained from the Prairie Adaptation Research Collaborative (PARC; www.parc.ca). Razavi et al. (2016) describe the tree-ringtree-ring measurement, detrending and averaging procedures used. The tree-ringtree-ring chronologies used represent tree growth rates from 1600 to 2001.

Field Code Changed

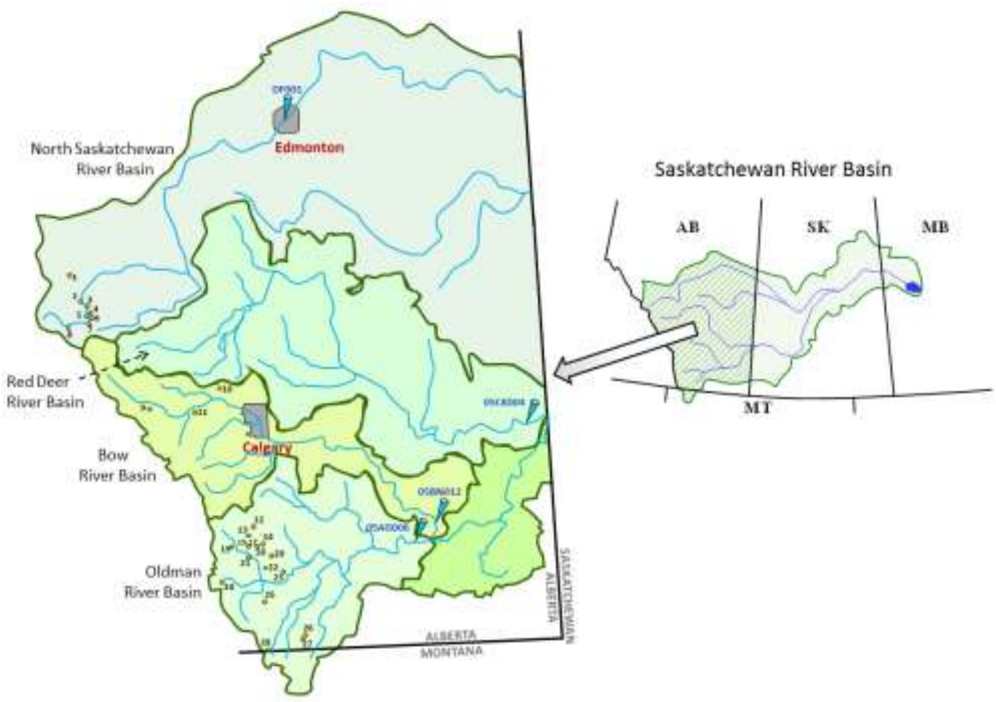

Figure 1. Map of the tributaries of the Saskatchewan River Basin and the locations of the chronology sites (circles) and streamflow gauges (cones)

2.3 Methodology

2.3.1 Reconstruction of flows based on ~~tree-ring~~tree-ring chronologies

The traditional method of reconstructing streamflow based on ~~tree-ring~~tree-ring chronologies is through correlations between ~~tree-ring~~tree-ring chronologies and observed streamflow at the yearly scale. However, as shown by Razavi et al. (2016), there are stronger correlations between ~~tree-ring~~tree-ring chronologies and streamflow at multi-year time scales. In addition, establishing correlations at multi-year time scales can be a viable method of overcoming the significantly higher persistence in ~~tree-ring~~tree-ring chronologies compared to streamflow without resorting to prewhitening techniques, which have been shown to result in a loss of information not related to autocorrelation (Razavi et al., 2016; Razavi and Vogel, 2017). The persistence present in tree-ring chronologies is due to a mixture of the persistence in the climate signal and the biological carry-over effects of trees, which for example, would allow trees to tolerate a water shortage in a dry year if the preceding year was wet. In addition, teleconnection signals typically occur in concert with precipitation in a region, and thus with water availability for tree growth. Therefore, tree-ring chronologies and their respective streamflow reconstructions should carry the teleconnection signals. As shown by Razavi et al. (2016), the persistence effect diminishes over a longer time scale. ~~-~~Although the relationship between streamflow and ~~tree-ring~~tree-ring chronologies strengthens at multi-year time scales, establishing this relationship at an optimal timescale that can be in the order of 5 years (Razavi et al., 2016) would disadvantage the process of disaggregation of ~~deconstructed~~ reconstructed flow. Therefore, as a compromise, the present study established statistical relationships between two-year moving averages of ~~tree-ring~~tree-ring chronologies and naturalised streamflows. Multiple linear regression (MLR) fitted by least squares was the statistical approach taken to establish the relationships between ~~tree-ring~~tree-ring chronologies and streamflows. We can expect a fairly linear relationship between flow and tree-ring growth as observed in many regions~~since both depend on soil moisture~~ of the world (Axelson et al., 2009; Boucher et al., 2011; Case & MacDonald, 2003; Gou et al., 2007; Souchyn & Ilich, 2017) ~~(REF)~~, and ~~(~~MLR~~)~~ is a simple but effective method of representing this direct monotonic (approximately linear) relationship between tree growth rate and flow. ~~Since both flow and tree-ring growth depend on soil moisture, we can expect a fairly linear relationship.~~ The predictive ability of the models was assessed through the coefficient of determination, R^2. Similar to Razavi et al. (2016), since the North Saskatchewan River and Oldman River sub-basins contained sufficient chronology sites, only the four and eight chronology sites falling within the sub-basins ~~of the North Saskatchewan River sub-basin and Oldman River sub-basin~~, respectively were used to establish their respective MLR models;~~,~~ whereas since few or no sites were present in the Red Deer River and Bow River sub-basins (Fig. 1), all 16 chronologies were used to establish their MLR models ~~for the Red Deer River and Bow River sub-basins (Fig. 1)~~. Building on the experience of Razavi et al. (2016) and employing the Akaike Information Criterion, models with both three and two chronology predictors (tree-ring stations) were established for the North Saskatchewan River and Oldman River sub-basins, whereas MLR models with only two chronology predictors were established for the Bow River and Red Deer River sub-basins. MLR models were generated for the shared period between ~~tree-ring~~tree-ring chronologies and naturalised streamflows of 1912–2001. A leave-one-out cross-validation strategy was used to test the performance of each model.~~-~~ Th~~e~~is validation-strategy maximises our ability in validating~~the validation of~~ the MLR models using the relatively short overlap period between the tree-ring chronologies and reference flow and provides a more accurate measure of model goodness of fit and can identify and avoid overfitting. To account for the uncertainty in streamflow reconstructions, multiple MLR models with the best performances were selected for each sub-basin. The choice of the best models for each sub-basin was rather subjective, and depended on relative R^2 values achieved for all the models generated.

2.3.2 Disaggregation of two-year reconstructed flows to weekly

Although there are definite advantages in reconstructing streamflow from ~~tree-ring~~tree-ring chronologies at multi-year time scales (Razavi et al., 2016), the usefulness of these flows for evaluating water resources systems is limited. Generating weekly reconstructed streamflow would be of more use in evaluating water resources systems as, for example, the established water management model, the Water Resources Management Model (WRMM) (Alberta Environment, 2002) used within the Prairie Provinces, runs on a weekly time step. The conceptual approach taken can be represented in Fig. 2. The basic premise adopted is that biennial reconstructed flow can be disaggregated to weekly reconstructed flow by the selection of biennial flow periods from the reference naturalised flow (1912–2001) (two-year instrumental periods) with similar attributes to the biennial reconstructed flow, after which the weekly flow distribution of the selected reference flow period can be used to construct the weekly flows. The attributes used to match the biennial reconstructed flow with biennial reference flow were hydrological condition, simply defined as dry, normal and wet conditions corresponding to flow less than the 25th percentile, between the 25th percentile and the 75th percentile, and greater than the 75th percentile, respectively, and which year in each biennial flow, year 1 or year 2, contributes the greater amount of flow. In Fig. 2, (1) represents the average ~~tree-ring~~tree-ring growth rates of all the ~~tree-ring~~tree-ring chronologies used to generate a particular MLR model for a sub-basin on a yearly time step. By examining the yearly tree-ring growth rates in pairs (on a biennial scale), it can be determined which yearly growth rate, that of year 1 or year 2, is larger. And since we constructed biennial flows from biennial tree-ring growth rates, t~~T~~his allows B for each biennial flow in (2) to be set to 1 or 2 to indicate whether the first or second year of that biennial flow value contributed the greater flow. ‘A’ in (2) represents the hydrological condition explained earlier. A similar process is performed for the weekly naturalised reference flow in (3), except that average yearly flows are used to set ‘B’. The biennial reconstructed flow is then stepped through in (4), and a similar period according to A and B is randomly selected from the biennial reference flow. The approach of random matching allows an ensemble of weekly flow reconstructions to be generated for each single biennial flow reconstruction while~~.~~ retaining the same underlying statistical properties. The weekly distribution of flows in the selected biennial reference flow period is then used to construct the weekly flow reconstruction, scaled to have the same biennial average as the original reconstructed biennial flow. An ~~good~~ argument could be made that the scaling should be according to the variance of the biennial reference flow; however, the variance of the reconstructed flow was found to be similar to that of the reference flow using this approach.

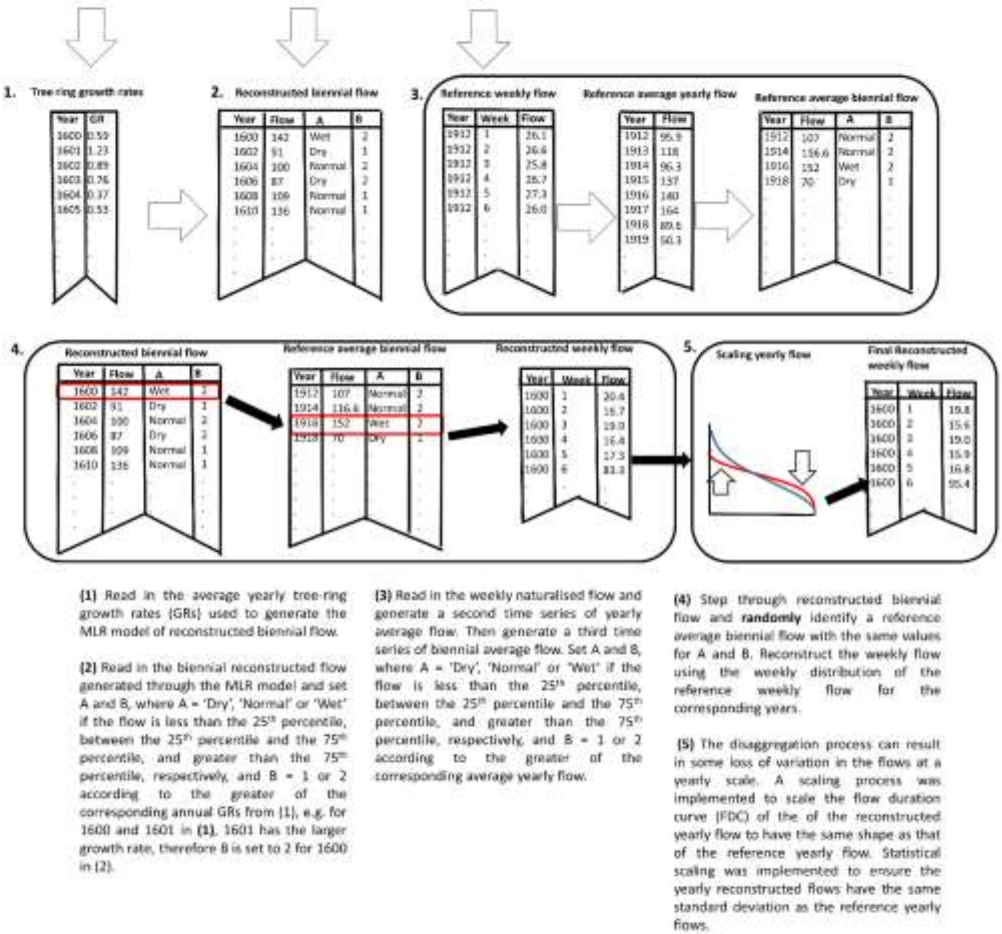

Figure 2. Conceptual representation of the process for disaggregating two-year (biennial) ~~tree-ring~~tree-ring reconstructed streamflow to weekly reconstructed streamflow

As expected, t~~T~~he biennial reconstructed time series ~~naturally~~ demonstrate smaller variability compared with the biennial flows in the reference period~~,~~ when MLR models are used for reconstruction, as the MLR models fitted by the least square method always produce smaller variance compared with the variance of observations. Therefore, the resulting annual and weekly time series also have less variability compared with their counterparts in the reference period. To rectify this problem, the reconstructed flows generated by stage (4) in Fig. 2 over the reference period (1912–2001) were compared to the reference flow at a yearly scale in the form of flow duration curves (FDCs). Typically, loss of variance in the reconstructed flows will manifest as fewer extreme high and low flows. A scaling equation was implemented to scale the FDC of the reconstructed flow to have the same shape as that of the reference flow:

$$q' = q \times (A \times P^B + C), \quad \text{(Eq. 1)}$$

where q' is the scaled yearly reconstructed flow ($m^3\ s^{-1}$), q is the yearly reconstructed flow ($m^3\ s^{-1}$), P is the ~~frequency~~ duration (%) and A, B and C are parameters that are calibrated by fitting the scaled yearly flow reconstructions for the reference period (1912–2001) to the yearly reference flow FDC.

In addition, the scaled yearly reconstructed flows were re-scaled according to the mean and standard deviation of the yearly reference flows:

$$q'' = \frac{q' - q'_{stdev}}{q'_{mean}} \times Q_{stdev} + Q_{mean}\ , \quad \text{(Eq. 2)}$$

where q'_{stdev} and q'_{mean} are the standard deviation and mean of the scaled yearly reconstructed flow for the reference period (1912–2001), respectively, Q_{stdev} and Q_{mean} are the standard deviation and mean of the yearly reference flow, respectively and q'' is the final (re-scaled) yearly reconstructed flow for the entire reconstruction period (1600–2001).

This update of the yearly reconstructed flows was~~is~~ used to scale the weekly flow reconstructions, which were~~are~~ in turn scaled to have the same biennial average as the original biennial flow reconstructions.

2.3.3 Comparisons of autocorrelation between weekly flow reconstructions and reference flow

Weekly reference flows and weekly reconstructed flows were averaged to yearly over the reference period (1912–2001) and autocorrelation was calculated for different yearly time lags from one to ten years. This was performed to confirm that the important statistical property of autocorrelation in the reference flows was carried over into the reconstructed flows.

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3 Results

3.1 Reconstruction of biennial flows based on ~~tree-ring~~tree-ring chronologies

MLR models with the best R^2 values for each sub-basin were chosen to reconstruct biennial flows based on ~~tree-ring~~tree-ring chronologies (Table 1). Four, nine, six and ten MLR models were chosen for the North Saskatchewan, Oldman, Red Deer and Bow sub-basins, respectively, with R^2 values ranging from 0.50–0.56, 0.44–0.51, 0.45–0.55 and 0.49–0.56, respectively.

Figure 3 shows the time series of reconstructed two-year (biennial) flows for all the MLR models shown in Table 1 for the four sub-basins along with the reference flow over the calibration period.

Table 1. Regression equations and R^2 values obtained in two-year (biennial) flow reconstructions using ~~tree-ring~~tree-ring chronologies for the Saskatchewan River Basin. Tree-ring ~~chonology~~chronology site code definitions can be found in Sauchyn et al. (2011).

Sub-basin	R^2	Multiple linear regression equation
North Saskatchewan	0.51	20.30 × SFR + 71.33 × DEA + 123.16
	0.56	40.42 × WPP + 64.04 × DEA + 112.48
	0.50	83.62 × DEA + 12.75 × TWO + 121.26
	0.52	21.61 × SFR + 62.09 × DEA + 14.66 × TWO + 116.74
Oldman	0.47	-39.24 × BDC + 93.32 × CAB + 66.06
	0.46	32.13 × WSC + 55.14 × HEM + 29.96
	0.44	64.79 × CAB + -18.03 × ELK + 68.11
	0.49	24.04 × OMR + -52.63 × BDC + 86.24 × CAB + 64.02
	0.49	-51.66 × BDC + 31.88 × WSC + 75.79 × CAB + 65.28
	0.51	-38.64 × BDC + 71.69 × CAB + 42.19 × HEM + 45.61
	0.48	31.64 × WSC + 70.46 × HEM + -33.73 × ELK + 45.80
	0.51	40.40 × CAB + 58.02 × HEM + -38.00 × ELK + 53.57
	0.49	42.32 × CAB + 43.94 × HEM + -17.24 × BZR + 48.39
Red Deer	0.55	-9.13 × SFR + 35.68 × WCH + 29.50
	0.45	-7.16 × WPP + 44.086 × OMR + 24.74
	0.46	-4.40 × WPP + 39.63 × WSC + 26.43
	0.50	-3.24 × WPP + 39.45 × WCH + 23.41
	0.46	-14.82 × WPP + 37.04 × JOLA + 37.81
	0.47	-0.001 × DEA + 37.39 × WCH + 23.05
Bow	0.53	31.49 × SFR + 40.42 × WSC + 54.93
	0.50	33.42 × SFR + 36.59 × CAB + 56.74
	0.50	36.67 × SFR + 53.75 × HEM + 36.18
	0.51	40.40 × SFR + 28.60 × WCH + 54.02
	0.49	26.48 × SFR + 56.23 × JOLA + 42.07
	0.50	34.49 × SFR + 35.19 × LEE + 56.20
	0.56	41.08 × WPP + 39.93 × WSC + 49.15

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0.53	42.38 × WPP + 35.25 × CAB + 52.53
0.50	44.72 × WPP + 49.00 × HEM + 36.40
0.55	37.33 × WPP + 56.48 × JOLA + 33.87

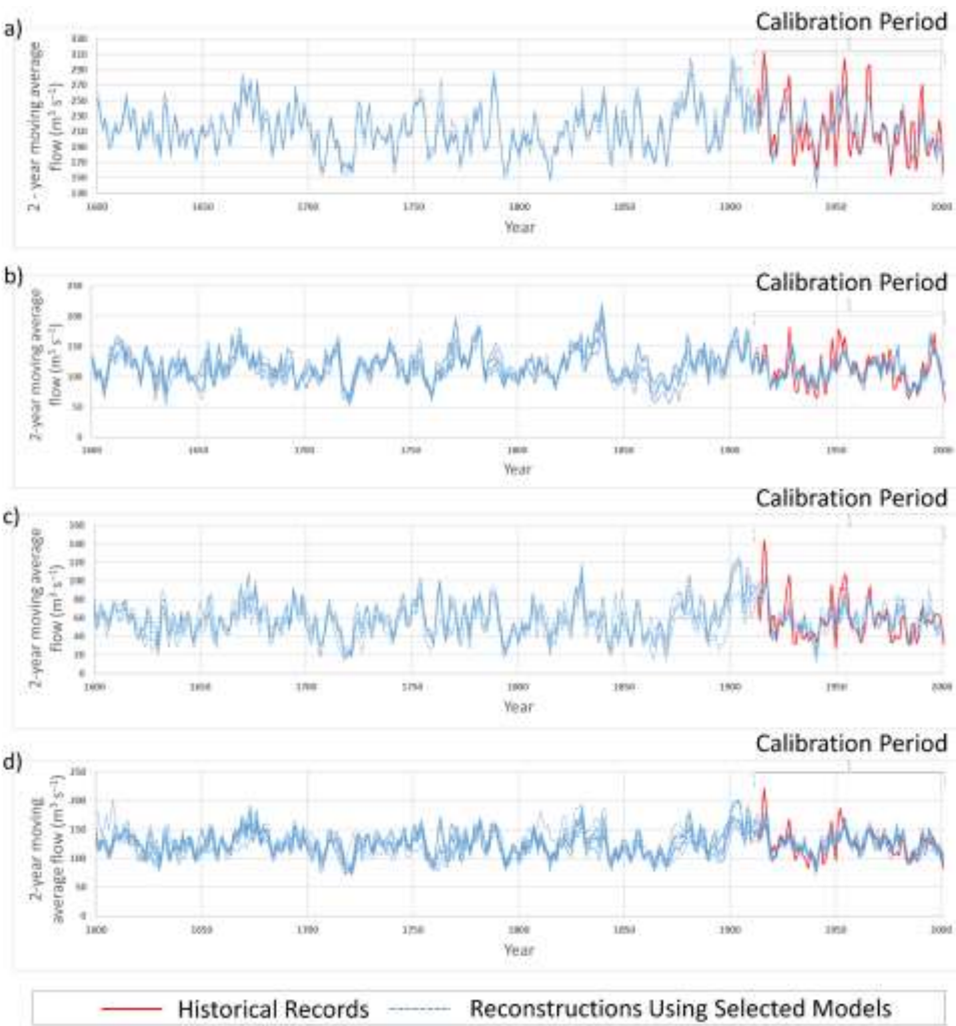

Figure 3. Time series of reconstructed 2-year moving average (biennial) flows in the (a) North Saskatchewan, (b) Oldman, (c) Red Deer and (d) Bow rivers. The shown reconstructed flows for the calibration period are the results of cross-validation

Figure 3 shows a relatively narrow distribution of reconstructed flows for the North Saskatchewan and Oldman sub-basins relative to those of the Red Deer and Bow River sub-basins, indicating a higher degree of uncertainty in the reconstructed flow for the latter pair of sub-basins. This could be related to the fact that the Red Deer and Bow River sub-basins contained few or none of the 16 ~~tree-ring~~tree-ring chronologies used in the biennial flow reconstructions.

3.2 Disaggregation of two-year (biennial) reconstructed flows to weekly

Figure 4 shows an example of how the scaling equation was derived for step (5) in Fig. 2 of the disaggregation process. This example is for the Bow River for one of the MLR models, and shows the FDCs of the yearly reconstructed flow up to step (4) and the yearly reference flow. The differences in the shapes of the FDCs illustrate some loss of variation in the reconstructed flows, with fewer extreme (high and low) flows. The values of *A*, *B* and *C* in Equation 1 were changed to obtain a scaling of the reconstructed flow FDC to take a similar shape to that of the reference flow.

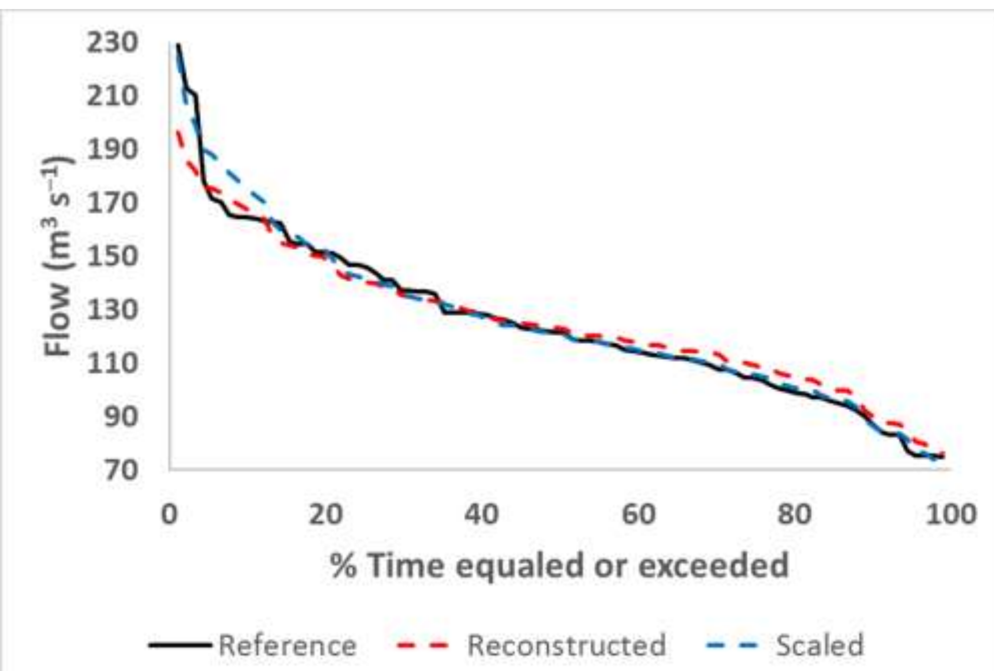

Figure 4. An example of a comparison between a yearly flow reconstruction and yearly reference naturalised flow for the reference period (1912–2001) for the Bow River using a flow duration curve (FDC). A scaling method was used to scale the yearly flow reconstruction FDC to have the same shape as the FDC of the yearly reference flow

For the present study, an ensemble of 30 weekly flow reconstructions for a single biennial flow reconstruction for each sub-basin was generated to illustrate the method. Fig. 5 shows the ensemble time series of the weekly flow reconstructions in relation to the reference weekly naturalised flow for a short window of the reference period for the Oldman River. It is evident that the reconstructed flows have the correct timing and similar range of flows to the reference flow, and also respond to periods of increased and decreased flow. However, further analysis was required to determine if the reconstructed flows have similar statistical properties to the reference flows.

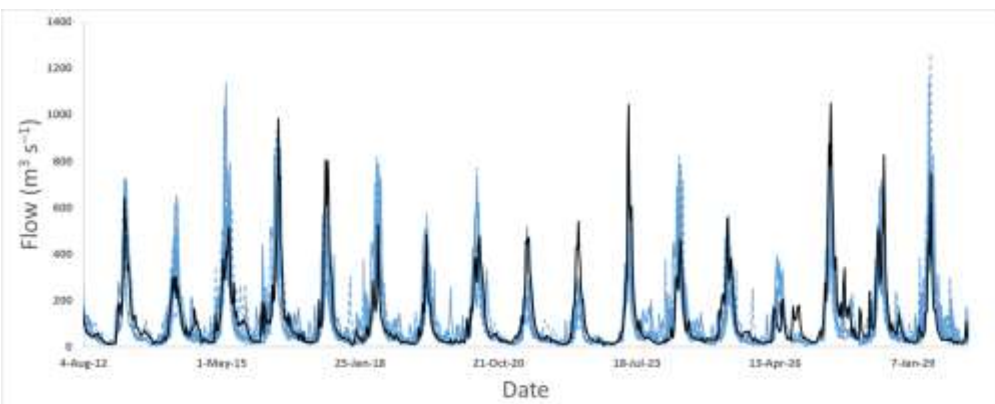

Figure 5. A time series comparison of an ensemble of 30 weekly flow reconstructions (dotted blue) and weekly naturalised flow (solid black) for the Oldman River basin.

Figure 6 shows the cumulative frequency distributions (CFDs) for the reconstructed flows in relation to the reference flows for a yearly time step, for both the reference period (1912–2001) and the full reconstruction period (1600–2001). The minimum and maximum bounds of the CFDs of the 30 reconstructed flows for the reference and full period are represented by the red dotted and blue dotted lines, respectively, whereas the CFD for the reference flow is indicated by the solid black line.

It is evident from Fig. 6 that for each sub-basin, the bounds of the CFDs for reconstructed flows for the reference period encompass the CFD of the reference flow. The bounds of the CFDs for reconstructed flows for the full period show some shifts in some cases compared to the reference flow. For example, the reconstructed flows for the Oldman River for the full period appear to be slightly higher than those of the reference period (Fig. 6b) whereas the reconstructed flows for the North Saskatchewan River over the full period may have a smaller proportion of high flows compared to the reference period (Fig. 6a). It is important to emphasise~~consider~~ that this example considers only one reconstruction model for each sub-basin, and Fig. 3 shows a fairly high variability between reconstructions for some sub-basins; therefore, the final set of flow reconstructions will contain considerably higher variability.

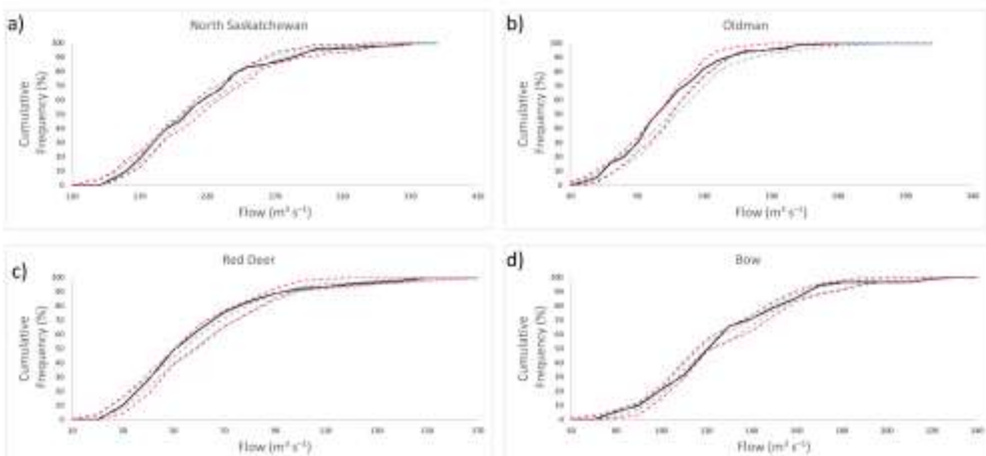

Figure 6. Cumulative frequency distributions (CFDs) between reconstructed flow and reference naturalised flow at a yearly time step. The minimum and maximum bounds of the CFDs of the 30 reconstructed flows for the reference and full period are represented by the red dotted and blue dotted lines, respectively, whereas the CFD for the reference flow is indicated by the solid black line. (a) North Saskatchewan River, (b) Oldman River, (c) Red Deer River, (d) Bow River.

Figure 7 shows a comparison of autocorrelation for reconstructed and reference flows for the reference period 1912–2001 at a yearly time step for each sub-basin, where the dotted red lines indicate the maximum and minimum of the autocorrelation values of the 30 flow reconstructions and the solid black line is the autocorrelation of the reference flow. It is evident in Fig. 7 for all sub-basins for both the reconstructed and reference flows, that for each sub-basin, the autocorrelations of the reconstructed flows are generally comparable with that of the reference flow.

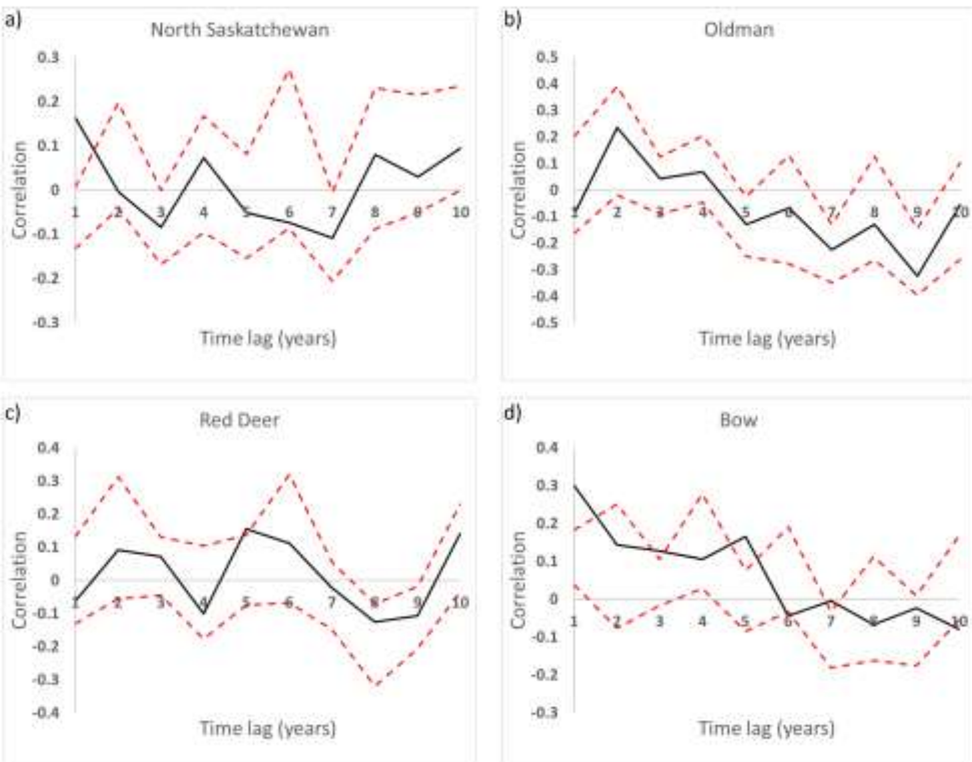

Figure 7. A comparison of autocorrelation between the 30 reconstructed flows and reference naturalised flow at a yearly time step over the reference period (1912–2001), where the red dotted lines indicate the maximum and minimum bounds of the autocorrelation values of the 30 reconstructed flows and the solid black line indicates the autocorrelation of the reference flow. (a) North Saskatchewan River, (b) Oldman River, (c) Red Deer River, (d) Bow River.

4 Discussion

Biennial reconstructions achieved for the four sub-basins in the present study were generally broadly similar to five-year reconstructions obtained for the same sub-basins by Razavi et al. (2016) using the same set of ~~tree-ring~~tree-ring chronologies. The major differences between the results of the present study and those of Razavi et al. (2016) are higher variation in the reconstructed flows and greater divergence between the reconstructed flows for individual sub-basins for the present study

(Fig. 3). This can be related to the fact that Razavi et al. (2016) found a stronger relationship between flow and tree-ringtree-ring chronologies on a five-year time step whereas the present study used a two-year time step. The R^2 values achieved for five-year flow reconstructions by Razavi et al. (2016) were in addition higher, ranging from 0.54 to 0.72, whereas R^2 values achieved in the present study ranged from 0.44 to 0.56. The present study established the relationship between flow and tree-ringtree-ring chronologies on a two-year time step as a compromise to more easily facilitate the disaggregation of flows while still achieving a relatively strong relationship between flows and tree-ringtree-ring chronologies and overcoming the discrepancies in persistence between flow and tree-ringtree-ring chronologies without resorting to prewhitening techniques.

While the MLR R^2 values obtained in the current study are within the range of those of previous studies describing the relationship between tree-ring chronologies and river flow, the present study did not aimfocus merely onto improvinge the regression fits., but ratherInstead, it introduceds a method that firstly constructs these relationships between tree-ring chronologies and naturalised flow in a way that preserves persistence properties and variability of hydrological time series, and secondly introducesd a novel method of disaggregating biennial reconstructed flow to weekly flows. The uncertainty, firstly in the relationships between tree-ring chronologies and naturalised flow, and secondly within the disaggregation technique, is addressed through an ensemble approach, by producing a range of viable MLR models for individual catchments and multiple plausible flow time series within the disaggregation.

The selection of the number of regressors in the present study was based on a former study with the same data (Razavi et al., 2016) where the Akaike Information Criterion was used to limit the risk of over-parametrization and over-fitting. The possibility of some level of collinearity among the tree-ring chronologies is however acknowledged. Although not reported here, principal component analysis (PCA) was applied to the tree-ring chronologies and results of MLR with and without PCA were compared, with no noticeable difference found.

The tree growth and water availability, as represented by tree-ring width and streamflows here, respectively, are always positivity correlated in moisture-limited settings (although this is not necessarily true in energy-limited settings). This means that a regression coefficient in a single linear regression should always be positive. However, as evident by the negative coefficients of the MLR models shown in Table 1, in multiple linear regression, the signs of some of the coefficients might become negative because of collinearity, which relates to the dependence of the tree-ring chronologies. The physical meaning of negative coefficients may be questionable. The application of principal component analysis (PCA) to the repgressors before doing regression is thea way only method of circumventing collinearity and avoiding negative coefficients in the models. , Although not reported here, PCA was applied to the tree-ring chronologies and results of MLR with and without PCA were compared, with no noticeable difference found.

but since applying PCA would not have improved predictive power of the regression in this case, PCA was not conducted.The possibility of some level of collinearity among the tree-ring chronologies is however acknowledged. Although not reported

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here, principal component analysis (PCA) was applied to the tree-ring chronologies and results of MLR with and without PCA were compared, with no noticeable difference found.

We note that tree rings provide no meaningful information on sub-annual variability. Within Therefore, the process of disaggregating two-year (biennial) tree-ring reconstructed streamflow to weekly reconstructed streamflow (Fig 2)is merely statistical, based on the information on the seasonality in the reference record., in step 3, the yearly average is affected by seasonal variations in flows. However, at this point in the disaggregation, a relationship between the reconstructed flows and reference flows at a biennial scale is being made. Therefore, the seasonal variation at this point is not considered. We note that tree rings provide no meaningful information on sub-annual variability. However, the influence of these much larger flows can be carried into the reconstructed weekly flows during step 4 in Fig. 2. As such, a caveat of this approach is the absence of information on any possible change in seasonality due to climate change effects. A good argument can be made that this approach may undermine the estimated intra-year variability of reconstructed flows, particularly within the context of climate change. However, the intra-year variability of flows cannot be determined from tree-ring reconstructed flows, and rather the reconstructed weekly flows will contain the long-term inter-year variability of flows as represented in the tree-ring data. Arguably though, from a water resources modelling perspective, theeis longer-term inter-year variability is more important to represent than intra-year variability; for example, it would be persistent long-term droughts that challenge the robustness of water resource systems. The discussion below shows that statistical properties of the reference flows are preserved in the reconstructed flows. This is important as the outcomes of modelling studies that would use these flows will depend largely on the presence of these statistical properties.

The approaches of using the weekly distribution of the reference flow within the disaggregation of biennial reconstructed flows [see Fig. 2 step (4)] along with the scaling of the yearly reconstructed flow [see Fig. 2 step (5)] appear to resolve the issue of discrepancies in variation and persistence between the reconstructed and reference flow. Figure 5 shows that the weekly reconstructed flow displays the same timing and range of flow in comparison to the reference flow, and also similar timing of dry and wet periods. Figure 5 and Fig. 6 show that the disaggregation approach used was successful in replicating the variance in the reference flow within the reconstructed flow. The persistence between flows for both the reference and reconstructed flows were similar, and both showed a generally decreasing trend with increasing time lag (Fig. 7).

Razavi et al. (2016) showed that tree-ring chronologies and flows at the annual time scale may possess inconsistent persistence properties. This inconsistency leads to dissimilar patterns of change and variability in the two types of time series across other time scales, which might invalidate any resulting flow reconstructions. To investigate this, the higher persistence in tree-ringtree-ring chronologies compared to flow can be transferred to reconstructed flow if the relationship between tree-ringtree-ring chronologies and flow is established at shorter time periods of a couple of years. However, the reconstructed flows and tree-ringtree-ring chronologies show more consistent persistence properties at longer time scales. Figure 8 shows the variance of the reconstructed and reference flows at different time scales on a log–log scale for the four sub-basins. The variance values at different time scales were calculated through averaging, so for example, a flow period of 100 years would yield 50 and ten values when the average of every two and ten years is calculated, respectively. The graph represents variance of the different time series over different time scales. The slopes of the different time series can be benchmarked against a random process (the red dotted line in the plot) which contains no persistence at any time scale. The differences in slopes between the reconstructed and reference flows shown in Fig. 8 compared to that of the random process can be attributed to persistence at the range of time scales represented. Razavi et al. (2016) using a similar plot showed that tree-ringtree-ring growth rates have considerably different persistence at shorter time scales compared to flow, and this persistence could be expected to be transferred to flow reconstructed from tree-ringtree-ring chronologies using relationships established at shorter time scales. The slope associated with reference flow would however be closer to that of the random process at a shorter time scale. Figure 8 demonstrates that the flow reconstruction and disaggregation method used in the present study appears to overcome the problem of transferal of higher persistence in tree-ringtree-ring chronologies to the reconstructed flow at shorter time scales. The slopes of both the reference and reconstructed flows appear to be similar to the random process, represented by the straight red line, at shorter time scales, after which their respective slopes follow similar trajectories as they diverge from that of the random process. This indicates that the reconstructed flows have similar persistence to the reference flows across the entire reference flow period of 90 years. Variance versus time scale plots provide a method of studying the 'Hurst Phenomenon' for long-term persistence in hydrologic time series (Hurst, 1951).

The results show that statistical properties of the reference flows are preserved in the reconstructed flows. This is important as the outcomes of modelling studies that would use these flows will depend largely on the presence of these statistical properties. A good argument can be made that this approach may undermine the estimated intra-year variability of reconstructed flows, particularly within the context of climate change. However, the intra-year variability of flows cannot be determined from tree-ring reconstructed flows, and rather the reconstructed weekly flows will contain the long-term inter-year variability of flows as represented in the tree-ring data. Arguably, from a water resources modelling perspective, this longer-term variability is more important to represent than intra-year variability; for example, it would be persistent long-term droughts that challenge the robustness of water resource systems.

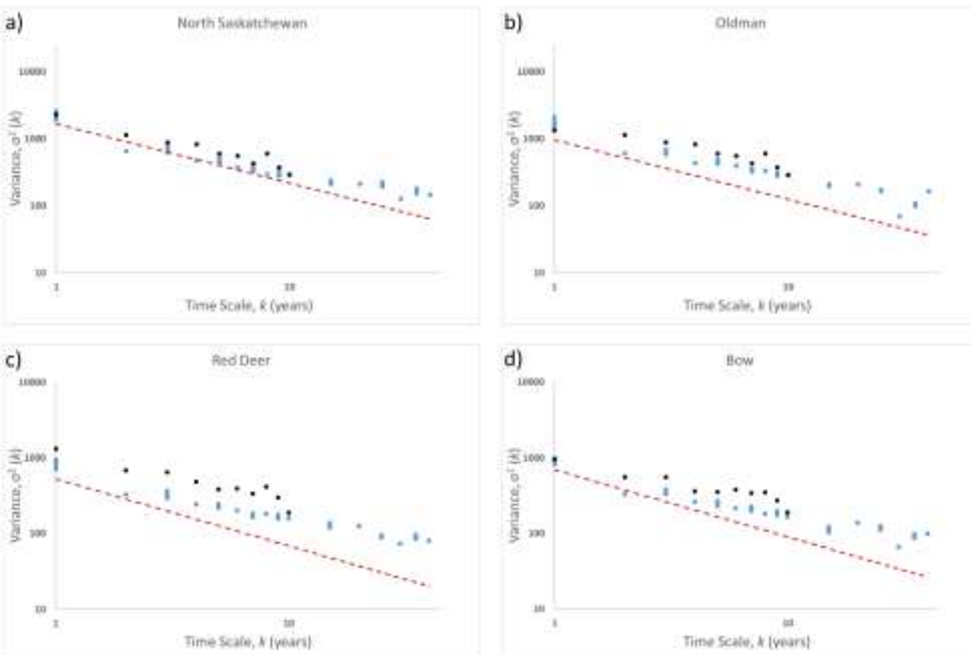

Figure 8. Variance-versus-time-scale plot for reference and reconstructed flows in the (a) North Saskatchewan, (b) Oldman, (c) Red Deer, and (d) Bow Rivers. Black and blue time series represent reference and reconstructed flows, respectively, whereas the red line represents a random process with no long-term persistence

The present study reconstructed biennial flows based on MLR models of the relationship between tree-ring chronologies and observed flow in the reference period, and an ~~good~~ argument can be made that changes in recent physical processes due to climate change could have distorted this relationship. Indeed, with increasing snow melt under a warming climate, the underlying statistical properties of flow in a water tower-driven catchment such as the SaskRB may indeed change considerably compared to the pre-reference period. However, since the reference period used ended in 2000, which is now almost 20 years ago, we ~~must~~ assume that the more recent climate change trends were absent or at least much weaker prior to the turn of the century.

In the present study, the reconstructions of biennial flow for the North Saskatchewan and Oldman River sub-basins showed lower divergence compared to those for the Red Deer and Bow River sub-basins (Fig. 3). This indicates a higher degree of uncertainty in the flow reconstructions for the Red Deer and Bow River sub-basins, and is due to the fact that few or none of the 16 ~~tree-ring~~tree-ring chronologies used occurred in these sub-basins. There are many additional uncertainties in the statistical relationships constructed between flow and ~~tree-ring~~tree-ring chronologies (Razavi et al., 2016). These uncertainties are amplified by the further disaggregation of biennial flow reconstructions to weekly. An approach to represent this uncertainty is to generate a large reconstructed flow ensemble. Uncertainty within the statistical relationship between flow and ~~tree-ring~~tree-ring chronologies can be represented by using multiple acceptable MLR models. For each biennial reconstructed flow generated by a single MLR model, the uncertainty in the disaggregation process can be represented by generating a large number of weekly reconstructed flows. In the present study, the number of weekly reconstructed flows generated for each acceptable MLR model was chosen to obtain an ensemble of 500 weekly flow time series for each sub-basin. To demonstrate the full range of uncertainty of the reconstructed flows, Fig. 9 shows the yearly average flow range (5th and 95th percentiles) of the 500 time series of weekly reconstructed flows for each sub-basin. It is evident that the higher uncertainty between reconstructed biennial flows, as represented in Fig. 3, results in higher uncertainty in the weekly flow reconstructions, as represented in Fig. 9. For example, there are relatively little differences between the biennial flow reconstructions for the North Saskatchewan River (Fig. 3a), and this results in relatively smaller uncertainty in the weekly flow reconstructions (Fig. 9a), whereas the large uncertainties in the biennial flow reconstructions for the Red Deer (Fig. 3c) translate into larger uncertainty in the corresponding weekly flow reconstructions (Fig. 9c). In general, Fig. 9 shows that there is a large uncertainty range in the weekly flow reconstructions. Reducing the total uncertainty in the weekly flow reconstructions therefore requires establishing stronger statistical relationships between the reference biennial flow and biennial tree-ring chronologies for each sub-basin. If new ~~tree-ring~~tree-ring chronology data falling within the Red Deer River and Bow River catchments become available, future studies could attempt to establish stronger statistical relationships with the reference flow for these two sub-basins.

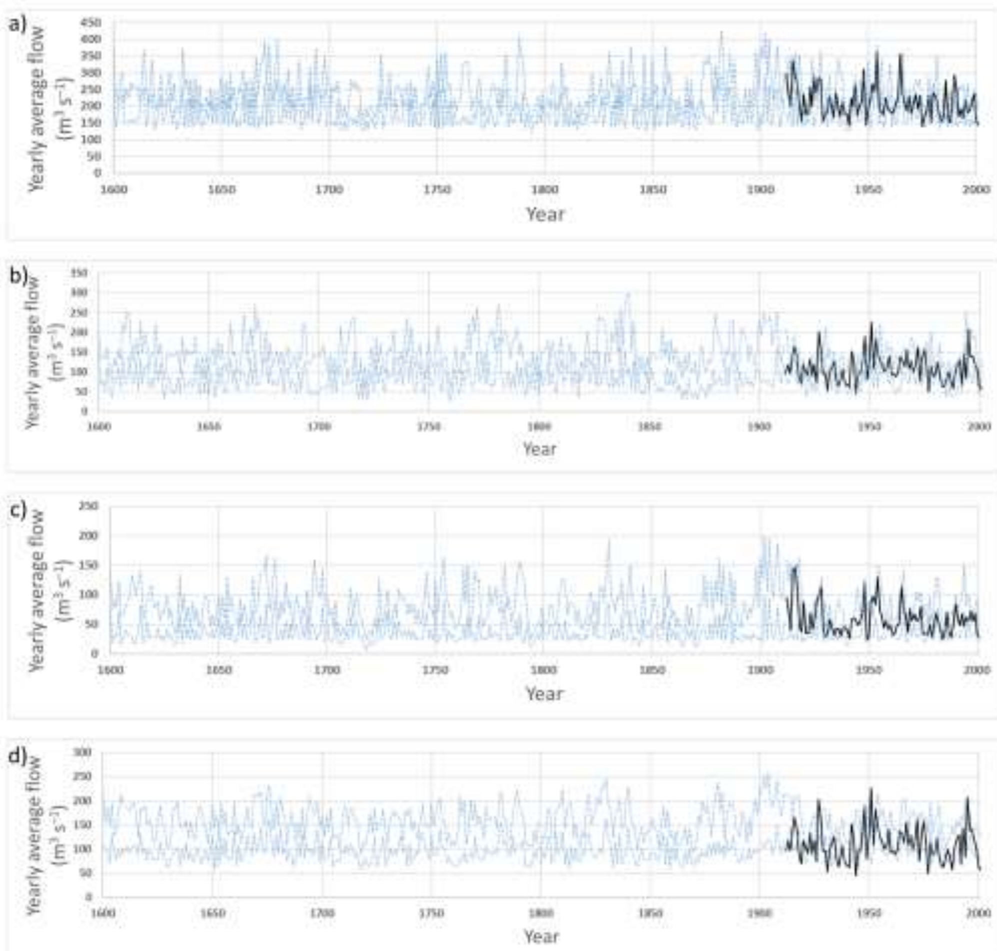

Figure 9. Time series of reconstructed yearly average flows in (a) North Saskatchewan, (b) Oldman, (c) Red Deer and (d) Bow rivers showing the 5th and 95th percentile range of the ensemble of 500 time series flows as a representation of uncertainty for 1600–2001 (dotted blue lines) as well as the observed reference flow (solid black line).

6 Data availability

The data generated in this study is available from https://doi.org/10.20383/101.0139 (~~in~~ Slaughter &~~and~~ Razavi, ~~(~~2019) ~~within in ????? repository~~.

7 Conclusions

This ~~e present~~ study presented a novel method for generating weekly flows for a period preceding the period of record, based on ~~tree-ring~~tree-ring data, while maintaining the statistical properties of the reference (measured) flows, including variability and persistence across all time scales. The method featured two novel components; unlike the conventional approach that mainly bases the analysis on annual (or sub-annual) flow-chronology correlations, the method (I) first reconstructs flows on a biennial (two-year) scale which demonstrates higher correlation with chronologies (tree growth), thereby resulting in a higher explanatory power, and (II) then disaggregates the biennial flows into annual and weekly scales based on information contained in the annual chronologies and weekly flow data in the reference period. The weekly reconstructed flows for the Saskatchewan River Basin, a large river basin in Western Canada which is of great social and economic importance, facilitates the investigation of multiple flow futures, which can contribute to increasing the resilience of the basin to future climatic changes.

Author contribution

SR provided supervision for all aspects of the study and critically evaluated the methods and results as well as the manuscript. SR specified the statistical techniques used, a broad concept of the disaggregation technique and methods to validate the results. AS conducted all analyses, wrote the code for the disaggregation technique and prepared the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

Special issue statement

This is a contribution to the special issue on water, ecosystem, cryosphere, and climate data from the interior of Western Canada and other cold regions

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Program for Canada (IMPC) and the Global Water Futures (GWF). The ~~tree-ring~~tree-ring data used in this paper are archived in the International ~~Tree-Ring~~Tree-ring Data Bank (ITRDB), available online at http://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring.

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