



RECONSTRUCTIONS OF HYDROLOGIC VARIABLES IN THE NORTH PLATTE RIVER BASIN

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Abstract:

Reconstructions of hydrologic variables are commonly created using tree-ring chronologies (TRCs) to generate information about historic climate and potential future variability. This study used TRCs to reconstruct annual streamflow, April 1st Snow Water Equivalent (SWE), and soil moisture in the North Platte River Basin (NPRB). Stepwise linear regression was performed to determine which of the 55 moisture sensitive TRCs were the best predictors of hydrologic variation. The regressions explained 63% of the variability in streamflow, 55% of the variability in SWE, and 66% of the variability in soil moisture. This study then maximized the overlapping period of records which resulted in a decrease in the percent of variability explained but indicated that the regression models were stable for long reconstruction periods. This study successfully reconstructed all three hydrologic variables for NPRB to 1438 or earlier. Temporal wet and dry periods for streamflow and SWE were closely aligned while soil moisture did not follow similar temporal patterns. This was likely due to a natural “lag” between soil moisture and streamflow / SWE given soil moisture tends to retain antecedent signals. The availability of reconstructed hydrologic data in NPRB allows for a better understanding of the long-term hydrologic variability in the region.

Keywords: Hydrologic Reconstruction; Streamflow; Snow Water Equivalent; Soil Moisture; Tree Ring Chronologies; North Platte River Basin.

Cite This Article: Sally Rose Anderson, Amanda Bowen, Glenn Tootle, and Abdoul Oubeidillah. (2019). “RECONSTRUCTIONS OF HYDROLOGIC VARIABLES IN THE NORTH PLATTE RIVER BASIN.” *International Journal of Engineering Technologies and Management Research*, 6(2), 59-71. DOI: 10.5281/zenodo.2587421.

1. Introduction

Hydrologic variables are essential factors when evaluating the overall climatic condition of a watershed. Streamflow, April 1st snow water equivalent (SWE), and soil moisture are three of the predominant hydrologic variables in the North Platte River Basin (NPRB). The availability and sustainable use of surface water are major issues in the western United States (U.S.). Deficiencies in long-term streamflow data hamper sustainable water resource management which relies heavily on detailed information associated with natural hydroclimatic variability (Watson et al. 2009). In 1993, Loaiciga et al. reviewed the methodology and applications of streamflow reconstructions using tree rings and found that ring widths in climate sensitive trees can be reliable indicators to

describe past hydroclimatic conditions. The estimated magnitude and duration of hydrologic droughts from streamflow reconstructions using tree-ring records are important water management resources and provide a strong link between dendrochronology and hydrology (Meko et al. 2012).

Longer and more robust streamflow reconstructions help to provide additional information on present and future extreme dry and wet events (Meko et al. 2007). Successful streamflow reconstructions have been conducted across the western U.S. using tree ring chronologies (TRCs) and have been used for assessing hydrologic drought scenarios (Cook et al. 1999; Meko et al. 2001). Several studies have reconstructed streamflow in the regions surrounding the NPRB (Woodhouse et al. 2006; Meko et al. 2007; Watson et al. 2009; Barnett et al. 2010) and Soukup et al. (2009) performed long lead-time forecasting in the NPRB for unimpaired streamflow stations.

When evaluating streamflow reconstructions, it is also beneficial to look at SWE and soil moisture values. Runoff from snowpack, which is influenced by soil moisture levels, occurs during the spring and early summer. April 1st SWE is commonly used to represent the maximum seasonal snowpack (Woodhouse 2003; Kuhn 2005; Timilsena and Piechota 2008). Early summer snowmelt from mountains in northern Colorado and southern Wyoming is the primary source of streamflow in the North Platte River (Shinker et al. 2010). Variability in North Platte SWE drives variability in streamflow and water availability for the Colorado River Basin.

Soil moisture is a key factor in the conversion process of precipitation into runoff and groundwater storage and, in that manner, is influential in the development of wet or dry periods (Tang and Piechota 2009). In temperate climates, the growth of trees closely depends on the heat and moisture availability of soil, making TRCs a useful predictor for reconstructions of past environments (Yin et al. 2008). Evans and Trevisan (1995) developed a water-balance “bucket” model which illustrated how variations in soil moisture transform the structure, species composition, and abundance of vegetative coverage. Fan and van den Dool (2004) produced a soil moisture dataset from 1948 to present based on the one-layer “bucket” water balance model. This dataset provides monthly soil moisture, evaporation, and runoff data for a $0.5^\circ \times 0.5^\circ$ global grid.

In this paper, streamflow, SWE, and soil moisture are reconstructed for the NPRB using TRCs. These hydrologic variables are examined in conjunction with each other to identify relationships between the three. The reconstruction of these variables augments the existing limited records of hydrologic data and may provide significant benefits to water managers in the NPRB for analyzing the historical wet and dry periods.

2. Materials and Methods

2.1. Study Area

The NPRB is located in northern Colorado and southern Wyoming (Fig. 1). The headwaters of the North Platte River originate in the high basin of North Park (north-central Colorado) (Acharya et al. 2011). The North Platte River is a tributary of the Platte River and is considered a major drainage avenue for eastern Wyoming and western Nebraska (Shinker et al. 2010). The length of the river is approximately 1,152 km (716 mi) and the NPRB is approximately 80,031 km² (30,900

mi²) (USGS 2013). There are 34 SNOTEL stations, five soil moisture grid cells, six unimpaired streamflow gages and 55 moisture-sensitive TRCs within or adjacent to the watershed.

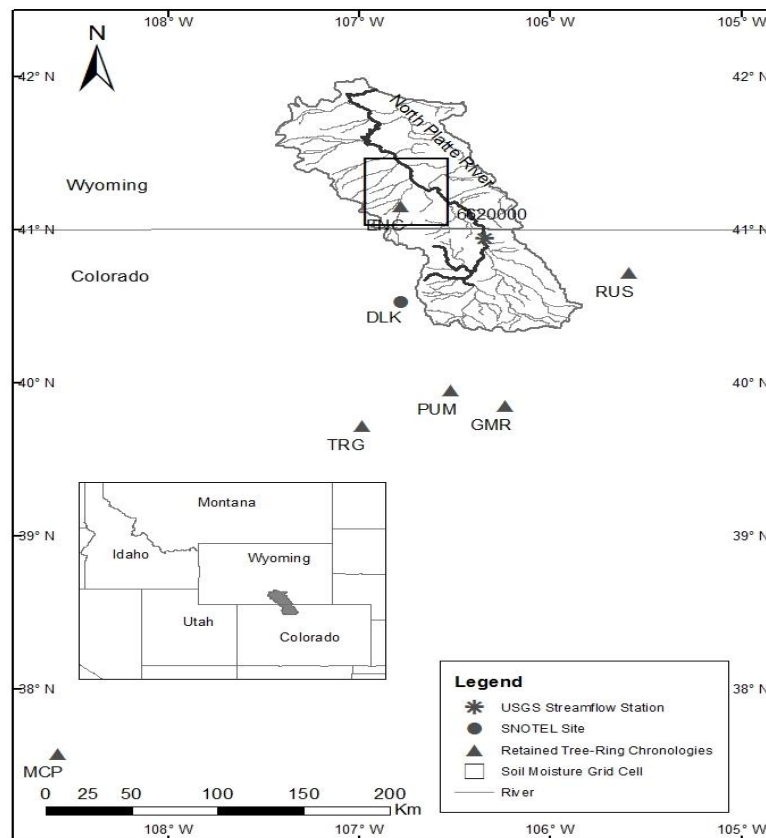


Figure 1: Map of the North Platte River Basin illustrating the location of the reconstructed USGS streamflow station, SNOTEL site, and soil moisture grid cell and the location of the retained tree-ring chronologies

2.2. Streamflow Data

The United States Geological Survey (USGS) collects surface water data across the U.S. Data are collected by automatic recorders and manual field measurements (USGS 2013). Slack et al. (1993) developed a Hydro-Climatic Data Network (HCDN) for streamflow gages that are relatively free from human influences, thus making them suitable for use in climate studies. Streamflow measurements from one of these gages (USGS 06620000, North Platte River near Northgate, Colorado; Fig. 1) were used in this study (<http://waterdata.usgs.gov/nwis/sw>). The station is located 2,381 m (7,810 feet) above sea level with a drainage area of 3,706 km² (1,431 mi²). The data at this station are recognized as unimpaired (Wallis et al. 1991). Streamflow units (million cubic meters, MCM) and water year measurements (October-September) are used.

2.3. SNOTEL Stations

SWE data were obtained from Snow Telemetry (SNOTEL) stations maintained by the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS)

website (<http://www.wcc.nrcs.usda.gov/snow/>). The SWE data consists of snow course data (measured by hand) and SNOTEL data (remotely sensed). The longest periods of record in the NPRB dates back to 1936. Of 34 SNOTEL stations located within the NPRB, 11 stations had complete records of April 1st SWE from 1940 to present. These 11 stations were selected for reconstruction.

2.4. Soil Moisture Data

Soil moisture data were collected from the National Oceanic and Atmospheric Administration (NOAA) website (<http://www.cpc.ncep.noaa.gov/soilmst/>). NOAA soil moisture data were estimated by a one-layer hydrological model (van den Dool et al. 2003). Fan and van den Dool (2004) modeled single-layer soil moisture at $0.5^\circ \times 0.5^\circ$ resolution from 1948 to present. The single-layer approach calculates soil moisture using a “bucket” water balance model where the input fields in the model are monthly global precipitations collected from the National Weather Service Climate Prediction Center and monthly global temperatures collected from Climate Data Assimilation System, jointly run by the National Center for Environmental Protection and the National Center for Atmospheric Research (Fan and van den Dool 2004). Five $0.5^\circ \times 0.5^\circ$ grid cells fall within the NPRB and were selected for reconstruction.

2.5. Tree-Ring Chronologies

For the majority of the western U.S., Meko et al. (1995) determined that tree ring widths are a proxy for gage records because the same prime climatic factors, namely precipitation and evapotranspiration, control both the growth of moisture-limited trees and processes related to streamflow. Fifty-five TRCs were used for the reconstruction of the three hydrologic variables examined in this study. These TRCs were obtained from the International Tree-Ring Data Bank website (<http://www.ncdc.noaa.gov/paleo/treering.html>), and are the same TRCs that were used in the previous hydrologic reconstructions in South Platte River Basin and western Wyoming (Woodhouse and Lukas 2006; Watson et al. 2009; Barnett et al. 2010; Anderson et al. 2012c). Residual TRCs were selected to reduce the possibility of low-order autocorrelation caused by changes in growth factors (Fritts 1976). Of the 55 TRCs, 14 were created from ponderosa pine (*Pinus ponderosa*), 22 from pinyon pine (*Pinus edulis*), 15 from Douglas-fir (*Pseudotsugamenziesii*), two from lodgepole pine (*Pinus contorta*), one from limber pine (*Pinus flexilis*), and one from Engelmann spruce (*Picea engelmannii*). All six of these species are considered to be moisture sensitive (Fritts 1976; Woodhouse and Lukas 2006).

2.6. Correlation and Stability Check

Statistical analysis is a method of determining the quality and suitability of TRCs for reconstruction of climatic variables (Woodhouse et al. 2006). Streamflow, SWE, and soil moisture were individually correlated with each of the 55 TRCs using Pearson’s correlation method (Timilsena and Piechota 2008). For temporal stability checks between TRCs and each of the hydrologic variables, correlation coefficients between the two were calculated for a 20-year moving window. TRCs that were positively and significantly correlated at a confidence of 90% or greater for all windows were retained. This process was repeated independently for streamflow, SWE, and soil moisture.

2.7. Regressions

Stepwise linear regression (SLR) is a common approach for the reconstruction of hydrologic variables using TRCs (Woodhouse 2003; Timilsena and Piechota 2008; Watson et al. 2009; Barnett et al. 2010; Anderson et al. 2012a). SLR uses a forward selection and backward elimination approach for regression analysis. Per Woodhouse et al. (2006), parameters were set with an alpha-to-enter value of 0.05 and an alpha-to-remove value of 0.10. Forward selection enters predictor variables (TRCs) into the model and retains the predictors that are statistically significant. Backward elimination determines which predictors are not statistically significant and rejects them from the model. This forward and backward selection approach continues until the model has selected the predictors that are the most statistically significant. After identifying the best predictor variables for each model, standard regression was performed.

The Durbin-Watson (D-W) statistic tests for autocorrelation among residuals from the regression model by determining whether or not the correlation between two adjacent error terms is zero. The D-W statistic ranges in value from 0 to 4. These ranges vary based on sample size and number of retained variables. Savin and White (1977) developed the significance table from which the D-W test statistic can be interpreted.

The variance inflation factor (VIF) is used to measure multicollinearity in a model. For models with more than one predictor variable, the largest VIF is analyzed. A VIF equal to 1 indicates there is no multicollinearity in the model. However, if the VIF is between 5 and ten, then the model is not considered statistically valid because the regression coefficients are poorly estimated.

The R^2 value indicates the percentage of variation explained with the regression equation and ranges from 0 to 1. The higher the R^2 value, the better the model represents the data. An R^2 value of 0.40 or higher is considered successful for hydrologic reconstructions (Woodhouse 2003; Timilsena and Piechota 2008).

Predicted R^2 values indicate how well a model predicts responses for additional observations and is used to prevent an overfitting tendency of the model. It explains the relationship between the predictor and response variable, although it fails to provide valid prediction in new observations. A predicted R^2 value significantly less than the R^2 value indicates that the regression model will not predict future responses based on new observations as well as the model fits existing data. Predicted R^2 values are calculated based on a drop one cross validation technique where one observation is removed from the datasets and the remaining observations are used to predict the missing value. The value for predicted R^2 ranges from 0 to 1.

2.8. Model Refinement

The overlapping periods of record between the TRCs and the hydrologic variables was limited by the fact that many of the trees used to develop the chronologies were cored in the late 1970s. For the preliminary reconstructions, this study used all 55 TRCs. The overlapping period of record started when the data for the hydrologic variable began and ended in 1978. For the subsequent reconstructions, this study selected the models from the preliminary analysis that yielded statistically strong results and refined them by maximizing the overlapping period between the

TRCs and the hydrologic variables. Since the preliminary analysis had already determined which TRCs were retained for each hydrologic variable, the subsequent analyses were based only on these retained TRCs. This allowed the overlapping period of record to be limited by the shortest end year of the selected TRC(s) rather than the shortest end year of all 55 TRCs. For example, in the preliminary reconstruction of streamflow performed in this study, the overlapping period of record was 1916–1978 (streamflow record began in 1916, the shortest of the 55 TRCs ended in 1978), and two TRCs (PUM and TRG) were retained. In the subsequent reconstruction of streamflow, two TRCs were considered (PUM and TRG) and the overlapping period of record was 1916–2002 (streamflow record began in 1916, the shortest of the two TRCs ended in 2002).

3. Results and Discussions

3.1. Streamflow Reconstruction

Fifty-five TRCs were correlated with streamflow data and tested for stability, resulting in four retained chronologies. These four TRCs were entered as predictors into the SLR model and two TRCs were selected. The reconstruction model using these two TRCs explains 63% of the variance in streamflow (Table 1). Previous studies of streamflow reconstructions in the surrounding areas yielded similar results, explaining 58–81% of variance (Woodhouse et al. 2006; Watson et al. 2009; Gray et al. 2011). In this study, the predicted R^2 value varies only 3% from R^2 value, indicating the reconstruction model is not overfitted. The D-W statistic reveals no autocorrelation, based on the significance table by Savin and White (1977). The VIF is below 5, suggesting the model is statistically valid.

3.2. SWE Reconstruction

Reconstructions were developed for the 11 SNOTEL stations with sufficient periods of record in the NPRB. The reconstructions explained 29 to 55% of variance for the various stations and used between 1 and 5 TRCs. The Dry Lake station (DLK) had the highest explained variance (55%) and is shown in Fig. 1 and Table 1. The 55 TRCs were individually correlated with DLK and tested for stability, resulting in 4 TRCs being entered into the SLR model. Three of these TRCs were retained. The reconstruction by Anderson et al. 2012c yielded similar results, explaining 58% of SWE variance for the Upper Green River Basin (UGRB). The predicted R^2 value for the DLK SWE reconstruction is within 10% of the R^2 value, indicating the model is not overfit. The D-W statistics shows significant auto-correlation is not present. The VIF is below 5, suggesting the model is statistically valid.

Table 1: Streamflow, April 1st SWE, and soil moisture regression statistics

Variable	Overlapping Period	Predictors	Retained	D-W	VIF	R^2	R^2 (predicted)
Streamflow	1916-1978	4	2	1.78	2.22	0.63	0.60
April 1 st SWE	1940-1978	4	3	1.76	1.89	0.55	0.44
Soil Moisture	1948-1978	17	3	1.26	1.36	0.66	0.55

3.3. Soil Moisture Reconstruction

Regression models were developed for each of the five soil moisture grid cells contained within the NPRB. The number of retained predictors varied between 1 and 3. The regression results for the five cells explained 36, 37, 40, 54, and 66% of variance in the soil moisture. The cell with the highest explained variance (66%) is centered at 253.25°W longitude and 41.25°N latitude and is shown in Fig. 1 and Table 1. The D-W statistic indicates no autocorrelation is present. The model is statistically valid having a VIF below 5. The model is statistically similar to the successful reconstruction of soil moisture by Anderson et al. (2012a) in the UCRB.

3.4. Refined Model Comparison

Once the preliminary regressions had been completed, the process was repeated with an aim to maximize the overlapping period. Only retained TRCs from the previous regression models of hydrologic variables were used in the SLR model. Although both the R^2 value and the predicted R^2 value declined from the preliminary regression models (Table 2), the refined regression models provide a longer overlapping period with the observed (streamflow, SWE, soil moisture) variables. The NPRB streamflow reconstruction, which begins in 1404, provides data for a longer period than the extended streamflow reconstruction of the main-stem Green River gage near Greendale, Utah produced by Barnett et al. (2010). The NPRB SWE regression results in a 560-year reconstruction of snowpack, which is longer than the existing snowpack reconstructions in the Colorado River Basin (Woodhouse 2003; Timilsena and Piechota 2008). The NPRB soil moisture reconstruction extends 510 years, which is longer than soil moisture reconstructions in the Upper Colorado River Basin (Anderson et al. 2010a).

Table 2: Streamflow, April 1st SWE, and soil moisture regression data for refined models

Variable	Maximized Overlapping Period	R^2	R^2 Predicted	Start of Reconstruction	TRCs Retained
Streamflow	1916-2002	0.57	0.54	1404	PUM, TRG
April 1 st SWE	1940-2000	0.48	0.41	1380	GMR, PUM, MCP
Soil Moisture	1948-1995	0.63	0.56	1438	ENC, PUM, RUS

3.5. Retained Tree-Ring Chronologies

The varying moisture sensitivity of different tree species is a significant controlling factor behind the variability of the reconstructed hydrologic variables (Anderson et al. 2012a). Previous research efforts attributed the difficulty of reconstructing hydrologic variables in the adjacent Green River Basin (Timilsena and Piechota 2008) and Wind River Basin (Watson et al. 2009) to the lack of moisture sensitive TRCs in the region. Within and adjacent to the NPRB, 55 moisture sensitive TRCs were available, which contributed to the success of the current reconstructions and compared favorably to the reconstructions of Woodhouse and Lukas (2006) in South Platte River Basin. In all of the reconstructions performed in this study, only six unique TRCs were retained (PUM, TRG, MCP, GMR, ENC, and RUS). Three of these TRCs (PUM, TRG, and MCP) were developed from pinyon pine cores, two (GMR, ENC) were developed from Douglas-fir cores, and one (RUS) was developed from ponderosa pine cores. The streamflow reconstruction relied solely on TRCs

developed from pinyon pines, the SWE reconstruction used TRCs developed from pinyon pines and Douglas-firs, and the soil moisture reconstruction used TRCs developed from pinyon pines, Douglas-firs, and ponderosa pines.

The geographic location of the moisture sensitive tree is an important indicator for capturing soil moisture in a given area (Anderson et al. 2012a). Ponderosa pines are the most widely distributed pine species in North America (Mast et al. 1998) and are generally found in the Rocky Mountains. Pinyon pines are found in cold, semiarid climate and are abundant in the lower mountainous region of western Colorado and extend to southern Wyoming (Evans, R. A. 1988). Douglas-firs are found in low and middle elevation forest areas of Colorado over a wide range of aspects, slopes, landforms, and soils (De Velice et al. 1986). Developing additional chronologies from pinyon pines across the NPRB could improve the skill of the streamflow, SWE, and soil moisture regressions as this species was useful in reconstructing all three types of hydrologic variables.

3.6. Comparison with Observed Hydrology

Observed streamflow was compared with reconstructed streamflow over the calibration period. Of the three driest years on record (1934, 1954, 1977), the observed and reconstructed values match fairly well for two of the years (1934, 1954), while for the third year (1977) the reconstruction portrays 1977 as being drier than the observed value. In the wettest years on record (1918, 1957, 1984, 1997), flows are consistently underestimated (Fig. 2a). This systematic underestimation of extreme high flow years is common in tree-ring studies (Gray et al. 2011). The resulting reconstructions generally provide a conservative estimate of wet events. The reconstructed annual streamflow (1404–1915) is higher than the observed flow (1916–2002), a result that was also identified in the updated streamflow reconstruction over the UCRB (Woodhouse et al. 2006). The reconstructed eastern Colorado Palmer Drought Severity Index (PDSI) at Cache la Poudre River at Canyon Mouth, Colorado (Woodhouse et al. 2002) was compared with the reconstructed streamflow from this study (Fig.3). The two datasets match well in the late-1600s, mid-1700s, and mid-1800s. Given the similar geographical location of these two studies, the comparable data trends give merit to these generated reconstructions.

Although 48% of the variance in SWE is explained by the model, this statistic does not provide an evaluation of how well the reconstruction represents extreme SWE values (high and low). Dry extremes are better replicated than wet extremes in moisture sensitive trees, as trees are limited in growth by dry conditions but not usually by wet conditions (Woodhouse 2003). Through assessment of the SWE calibration period, this study found that the reconstructed SWE closely modeled many of the driest years on record (1962, 1976, and 1994), although the reconstruction shows 1968 as being drier than the observed SWE (Fig. 2b). Reconstructed SWE for extremely wet years (1952, 1957, and 1978) is consistently low.

Observed and reconstructed soil moisture data were standardized (mean of zero, standard deviation of one) across the calibration period (Fig. 2c). Extreme high and low moisture levels are well represented by the reconstruction.

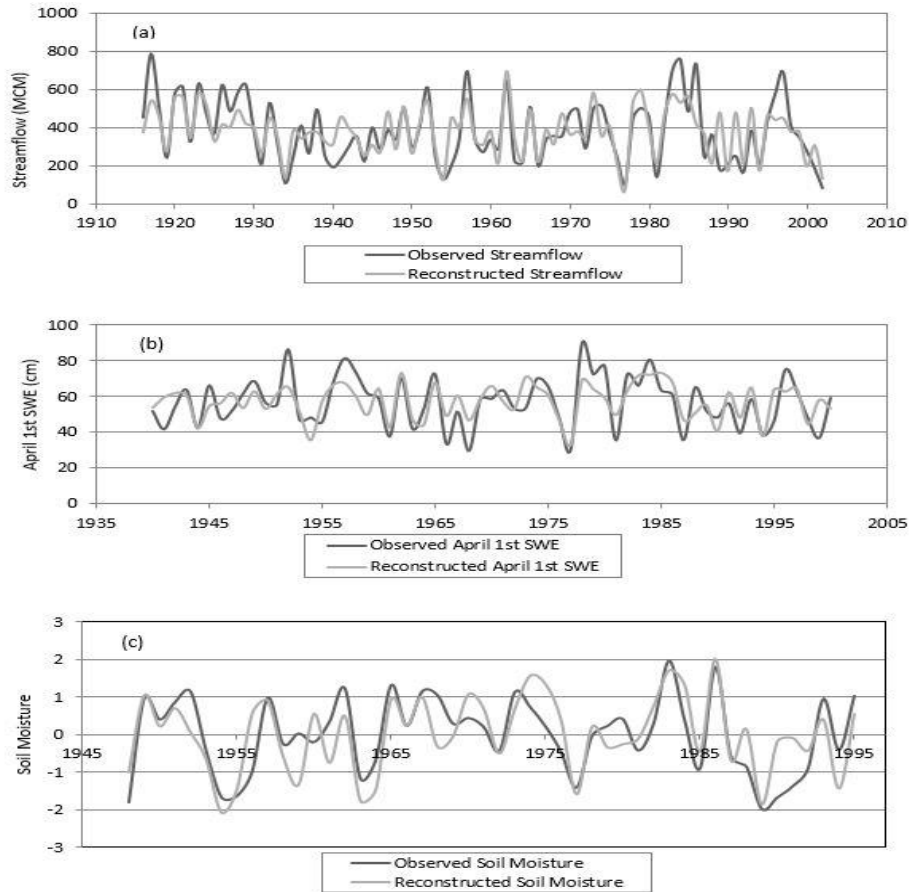


Figure 2: Graphical representation of observed vs. reconstructed hydrologic variables (a) streamflow, (b) April 1st SWE, (c) soil moisture (standardized)

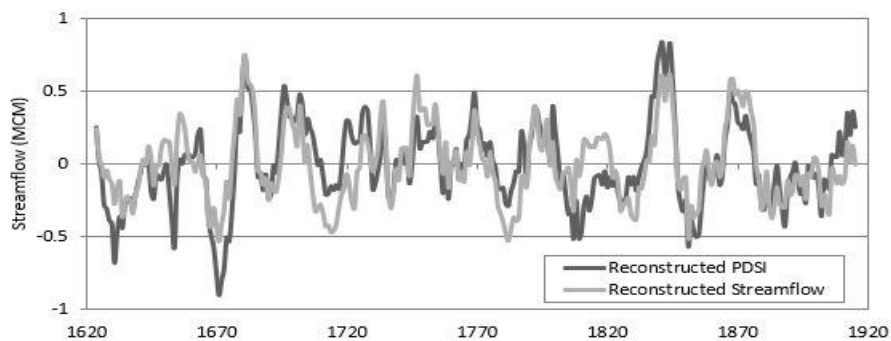


Figure 3: Comparison of reconstructed standardized Palmer Drought Severity Index (PDSI) (Eastern Colorado PDSI by Woodhouse et al. 2002) and reconstructed standardized streamflow (1615-1915), using a 10-yr filter

3.7. Climatic Variability of Hydrologic Variables in the NPRB

Reconstructions of hydrologic variables for the NPRB provide critical insight into the patterns of natural variability of streamflow, SWE, and soil moisture. These hydrologic variables are important when assessing the sensitivity of the North Platte River to current or future climate

change. The streamflow and SWE reconstructions created in this study cover five centuries. Similar to Anderson et al. (2012b), this study found a strong relationship between streamflow and SWE. Both reconstructions indicate that the years 1460, 1510, 1590, 1670, and 1850 were extremely dry and the years 1490, 1620 and 1680 were extremely wet (Fig.4). Changes in soil moisture can amplify climate extremes such as flood or drought (Tang and Piechota 2009). In four of the five years that streamflow and SWE reconstructions suggest were extremely dry (1460, 1590, 1670, and 1850), reconstructed soil moisture is very low. This indicates that soil moisture reconstructions can provide an insight into hydrologic droughts (Figure 4d).

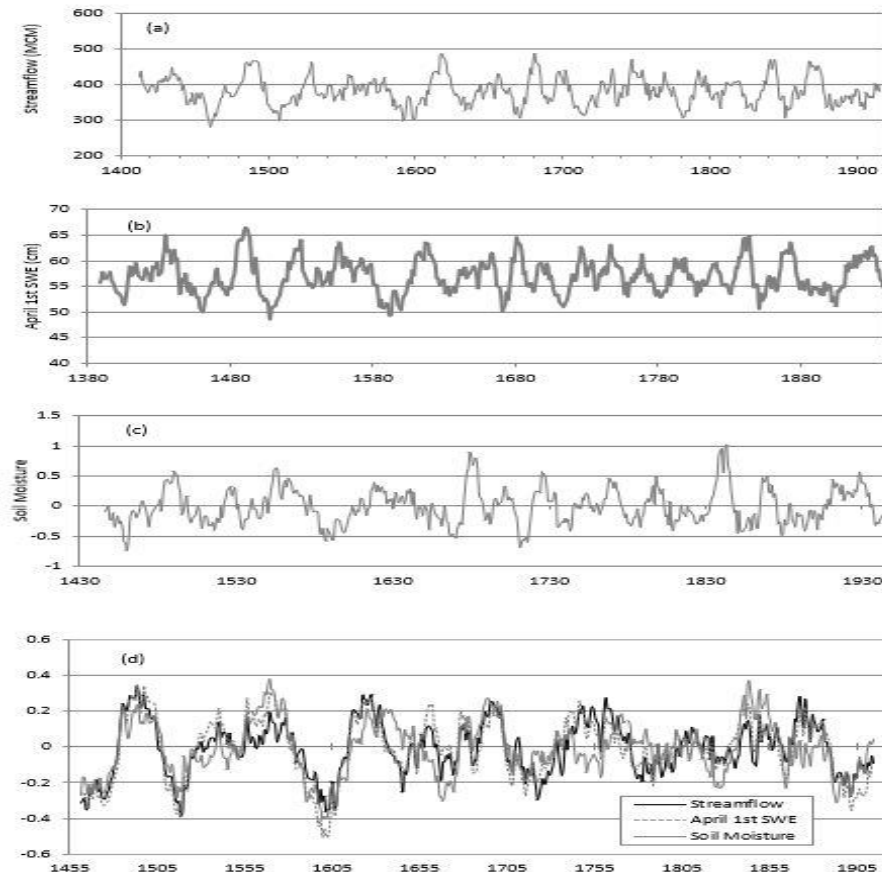


Figure 4: Graphical representation of reconstructed hydrologic variables (a) reconstructed streamflow using a 10-yr filter, (b) reconstructed April 1st SWE using a 10-yr filter, (c) reconstructed soil moisture (standardized) using a 10-yr filter, (d) standardized streamflow, standardized April 1st SWE, and standardized soil moisture using a 25-yr filter

4. Conclusions and Recommendations

Reconstructions of hydrologic variables are important factors for assessing the overall climatic scenario of a watershed and deducing the hydroclimatic variability in the western U.S. This study suggests that TRCs can be used as proxy records to represent hydrologic variables for a long-term perspective. The strong relationship between the streamflow and SWE reconstructions, and the fact that SWE volume directly impacts streamflow volume, suggests potential drought could be anticipated when the magnitude of spring snowpack is known. Future research should focus on

developing new TRCs in the NPRB and performing drought analysis (frequency, magnitude, duration and severity) to accurately denote extremes based on hydrologic reconstructions. It is possible that other hydrologic variables (i.e., precipitation, evapotranspiration) may have systematic long-term influence on tree growth in the NPRB, and this could be explored. Increased understanding of hydrologic patterns in the NPRB will provide insight to the water managers and engineers for planning the future adaptation and sustainability of the watershed.

Acknowledgements

This research is supported by the University of Wyoming Water Research Program funded jointly by the USGS, the Wyoming Water Development Commission, and the University of Wyoming. Additional support provided by the National Science Foundation Paleo Perspectives for Climate Change (P2C2) program award AGS-1003393.

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