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# An Annual Streamflow Reconstruction of the Red River, Kentucky Using a White Pine (Pinus Strobus) Chronology

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## Abstract

Using tree ring data (dendrochronology) a reconstruction of the historical annual stream flow of the Red River Basin of Kentucky was performed. Tree ring widths provide a surrogate record of the past climate and hence stream flow of a particular area, with thicker rings corresponding to wetter periods and thinner rings corresponding to drier conditions. This type of research is common in river basins across the western USA which are prone to serious droughts and flooding on annual and decadal scales. However, little research has been conducted in this manner in the eastern USA, Kentucky in particular, despite the potential for intermittent dry and wet periods over time. The use of the Daniel Boone National Forest is the focus of this study due to the well documented past flooding and drought events of the Red River during the 20th Century. The technique provided a reconstructed record from 1713 up to the end of the observed period in 1999. The results show that there has been a decrease in the number and frequency of prolonged wet and dry periods, although there has been an increase in the extreme wet and dry conditions during the later observed record which suggests a shift in the hydroclimatological regime of the river basin.

**Keywords:** dendrochronology, streamflow reconstruction, southeastern US

## 1. Introduction

Records of historical pluvial (wet) and drought (dry) conditions across the US typically originate from streamflow gauge records supplied by federal and state agencies, most notably the US Geological Survey (USGS). However, whilst the spatial coverage of these streamflow gauge records is fairly dense, especially for the southeastern region of the US, the temporal coverage rarely exceeds beyond the twentieth century.

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This provides a very limited dataset for water resources and river basin ecological management purposes. In particular current water resources management practices will determine future variability based on the short term gauged history (Woodhouse & Lukas, 2006a; 2006b; Milly et al., 2008). Almost no consideration of potentially more serious or changing conditions having occurred before the gauged period is taken into account due to a lack of readily available and accurate data. One of the major breakthroughs in this research area has been the development of dendrochronology in reconstructing historical streamflow beyond the gauged history of a river basin. This technique utilizes the annual tree rings present in moisture sensitive tree species as a surrogate record of various environmental conditions at the time of tree ring formation (Speer, 2010). Studies investigating the link between annual tree growth and streamflow began as far back as the 1930s in the US, although they were simple estimates of wet and dry conditions (Hardman & Reil, 1936; Hawley, 1937). One of the first studies to fully investigate the statistical relationship between tree rings and streamflow was conducted by Stockton & Jacoby, (1976).

They reconstructed the annual streamflow of the Upper Colorado River Basin at Lees Ferry in the southwestern US back to the year 1520 using regression between the gauged streamflow period and tree ring widths. Since this seminal study other researchers have reconstructed historical streamflow far beyond the gauged history for many regions across the western US, including the Upper Colorado (Woodhouse, Gray, & Meko, 2006; Barnett, Gray, & Tootle, 2010), Pacific northwest (Gedalof, Peterson, & Mantua, 2004; Wise, 2010), and California (Earle, 1993; Larson, 1994). The results of these and many other studies have been catalogued in the online TreeFlow system (2014). Despite the success in reconstructing historical streamflow across the western US, streamflow reconstructions are more limited in the southeastern/Atlantic US region. The climate of this region is generally wetter, experiencing a humid-subtropical climate compared to the more arid/semi-arid climate of the southwestern US, and many old-growth tree species have been cleared by logging and other management practices (Henderson & Grissino-Mayer, 2009). Another factor that has limited dendrochronological streamflow reconstructions across this region is the smaller sample of tree species suitable for dendrochronology. The western US is abundant in several moisture sensitive tree species, including the ponderosa pine (*Pinus ponderosae*) and Douglas-fir (*Pseudotsuga menziesii*). The southeastern US distribution of moisture sensitive species is more sporadic, focusing mainly on the scattered eastern hemlock (*Tsuga Canadensis*), white oak (*Quercus alba*), and white pine (*Pinus strobus*) species among others (Stahle, Fye, & Therrell, 2003).

Nevertheless, previous research has developed tree ring chronologies for past environmental reconstructions across the southeastern US. Blasing, Duvick, and West (1981) reconstructed May-June precipitation across eastern Tennessee and then expanded upon this research by reconstructing precipitation across the wider southeastern US region, identifying cyclical wet and dry periods, both more extreme than any previously recorded (Blasing, Stahl, & Duvick, 1988). In a more recent study, Henderson and Grissino-Mayer (2009) noted significant correlation between spring/summer precipitation and longleaf pine *(Pinus palustris)* growth across the southeastern coastal plain stretching from east Texas to South Carolina. Regarding streamflow reconstructions across the southeastern/Atlantic US, Cook and Jacoby (1983) successfully reconstructed June-August streamflow between 1730-1977 using five tree ring chronologies from multiple species for the Potomac River. This reconstruction was further extended to 950-2001 for May-September streamflow by Maxwell, Hessl, Cook, and Pederson (2011) which better replicated the mean and variance of the instrumental record and confirmed the presence of periodicity in the seasonal streamflow. Elsewhere a study by Cleaveland (2000) used chronologies obtained from Baldcypress (*Taxodium distichum*) trees to reconstruct June-August streamflow between 1023-1985 for the White River (Arkansas), discovering that the twentieth century experienced more extreme low flow events and a larger number of high flow events due to climatic and anthropogenic changes. The purpose of this research is to expand upon the limited tree ring database for the southeastern US by developing a tree ring site chronology to reconstruct the annual streamflow for the Red River, eastern Kentucky. Of particular interest are whether the record gauged drought and pluvial events have been exceeded during this extended history, and whether the occurrence and frequency of these events has been changing over the extended reconstruction.

## 2. Study Area

The Red River is located in eastern Kentucky as part of the larger Kentucky River system. The basin covers an area approximately 940km2 by the time it drains into Clay City (Figure 1). Upstream of this location, the river system drains through the Daniel Boone National Forest and Red River Geological Area, consisting of a mixed mesophytic forest distribution. The climate typically ranges from -7°C – 30°C between January and July with mean annual precipitation of 120cm (Woods et al., 2002).

The mean annual gauged flow (1939-2012) of the Red River at Clay City is 14m$^3$/sec, to give a mean annual streamflow volume of approximately 4.42MIL cubic meters.

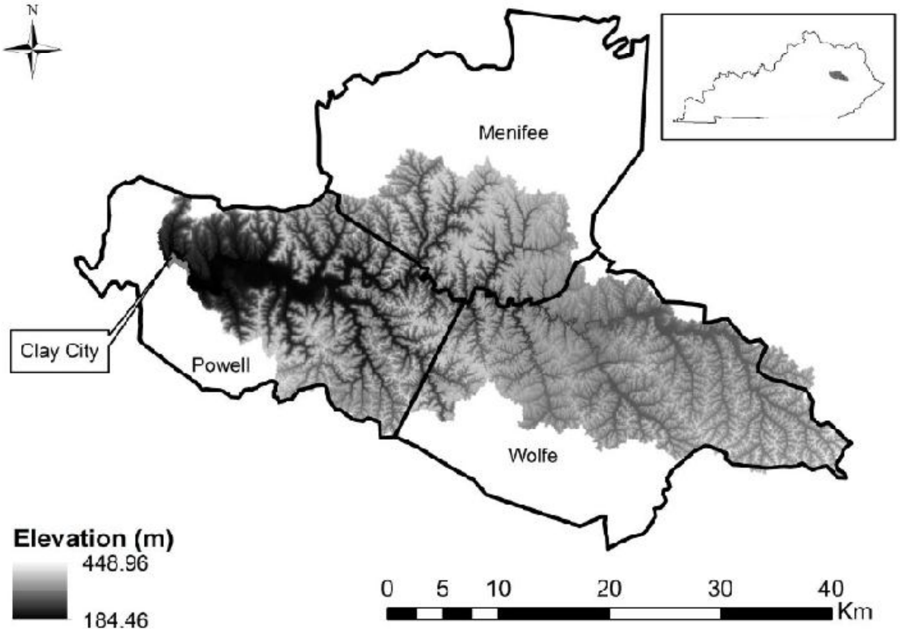


Figure 1: Red River Basin Elevation and Location within Kentucky

The Red River basin is of particular interest to this study for several reasons. The gauged hydrological history of the basin displays considerable variability due to an absence of flood control and diversion measures upstream. The Red River is also a significant tributary to the Kentucky River, itself a major tributary to the Ohio River system providing water resources to the eastern portion of Kentucky. Furthermore, the basin and surrounding area contains a widespread population of moisture sensitive trees which are particularly suited for dendrochronological analysis. However no tree ring site chronologies have presently been developed in this area. The Red River Gorge Geological Area is also home to the only known examples of the White-Haired Goldenrod plant (*Solidago albopilosa*), currently listed as a threatened species that too is sensitive to any environmental fluctuations (White & Drozda, 2006).

## 3. Data and Methods

### 3.1 Streamflow Data

The US Geological Survey provided an unbroken record of annual streamflow data (1939-1999) for the streamgauge located at the Red River outlet by Clay City, Kentucky (USGS #03283500). The mean annual discharge for each year was converted from a discharge in cubic feet/sec to a volume in cubic meters.

### 3.2 Tree Ring Data

As no tree ring site chronologies currently existed in the vicinity of the Red River Basin, a site chronology was developed by obtaining tree ring samples from 32 individual white pine trees (*Pinus strobus*) within the basin, in cooperation with the Daniel Boone National Forest Service. A 5mm Haglof Incremental borer extracted the core samples from each tree. Once extracted, the cores were left to dry for approximately one week, before being glued into specially prepared wooden core holders. Following this, sanding of each core took place using progressively finer grains of sandpaper ranging from 50 grit (125-149µm) to 400 grit (20.6-23.6µm) making individual tree ring identification easier (Speer, 2010).

Initial visual cross-dating of the cores labelled each tree ring with a specific year before measurement on a Velmex slide system allowing the identification of tree ring boundaries and ring widths accurate to 0.001mm. The system included a data logger for capturing and storing each tree ring measurement. The samples were then statistically cross-dated as a check against the visual cross-dating. In order to account for a naturally decreasing tree ring width trend signal as a function of increasing tree age and slower growth over time, each core was de-trended by fitting appropriate splines to generate a series of standardized tree ring chronologies. Each chronology was then checked for low-order autocorrelation (1-3 year lags) for removal by differencing. Finally the individual tree ring chronologies were compiled into a single site chronology using a robust bi-weight mean to reduce the effect of outliers from the individual chronologies (Fritts, 1976). The dendrochronological analysis software TSAP-WinTM performed the necessary steps towards building a site chronology beginning with the statistical cross-dating procedure (Rinn, 2011).

### 3.3 Streamflow Reconstruction

To reconstruct historical annual streamflow beyond the gauged period, linear regression was applied using the site chronology tree ring widths as the predictor variable with the annual streamflow volume as the predictand. Calibration and validation of the regression model used the split-sample procedure in which a portion of the observed record was withheld from calibration, and then utilized for the validation component in order to ensure the calibration and validation datasets were independent of one another (Woodhouse, 2003). In this study the model calibration utilized data for the period 1939-1978, and then validated for the period 1979-1999. Several statistical measures provided information on the fit and overall ability of the regression model to reconstruct observed annual streamflow volume, including $R^2$ (variance explained by the model), SE (standard error), RE (reduction of error- the validation equivalent of $R^2$), and RMSE (root mean square error).

## 4. Results and Discussion

### 4.1 Model Calibration and Validation

Figure 2 displays the observed versus reconstructed flow during the observed period. The regression model calibration and validation statistics are shown in Table 1, with basic descriptive statistics in Table 2. The statistics show that 53% of the streamflow variance is explained by the regression model, with an RE value of 0.40. The difference between the SE and RMSE is 10.1MIL cubic meters. These values are similar to those generated in other studies across the southeastern US. A comparison of the descriptive statistics verifies that while the model reconstructs a similar mean during the observed period, it underestimates both the maximum and minimum values, thus also giving a reduced variance/standard deviation.

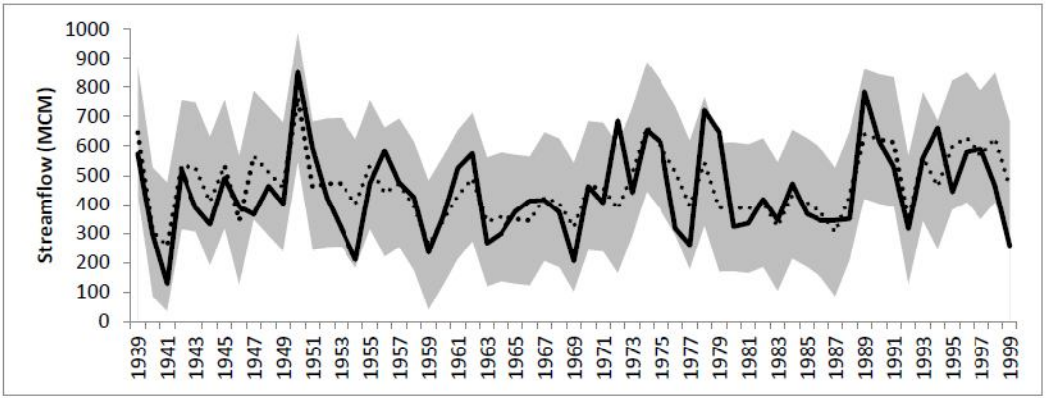


**Figure 2: Observed (Black) Vs. Reconstructed (Hatched) Streamflow 1939-1999. Gray Area Represents 95% Confidence Interval**

**Table 1: Calibration and Validation Statistics**

| Statistic | Calibration (1939-1978) | Validation (1979-1999) |
|---|---|---|
| Explained Variance ($R^2$) | 0.53 | |
| Reduction of Error (RE) | | 0.40 |
| Standard Error (SE) | 102.6MCM | |
| Root Mean Square Error (RMSE) | | 112.7MCM |

**Table 2: Observed Vs. Reconstructed Streamflow (MCM) Statistics 1939-1999**

| Statistic | Observed | Reconstructed |
|---|---|---|
| Mean | 443.7 | 460.3 |
| Median | 419.4 | 458.1 |
| Min | 128.2 | 255.4 |
| Max | 851.4 | 763.8 |
| Std. Dev. | 148.8 | 110.3 |
| Variance | 21774.1 | 11977.1 |

A further analysis of model skill classified each observed annual flow into quintiles that represented hydrological conditions (0.8-1.0 = very wet, 0.6-0.8 = wet, 0.4-0.6 = average, 0.2-0.4 = dry, 0-0.2 = very dry). The reconstructed annual flow classifications by quintile were then compared. Overall the model reconstructions successfully classified 46% annual flows, with 39% miss-classified by 1 quintile, and the remaining 15% miss-classified by 2 quintiles. These results suggest that the model is robust, having significant skill in reconstructing the observed annual streamflow.

### 4.2 Streamflow Reconstruction

Annual streamflow volume was reconstructed for 1713-1999 when applying the regression model (Figure 3). Table 3 displays the descriptive streamflow volume statistics for the observed (1939-1999) and reconstructed (1713-1938) periods. While the mean and median annual streamflow volumes were very similar between the gauged and reconstructed periods, the observed period experienced a greater variance in annual streamflow volume, confirmed by the larger standard deviation (SD) and greater range between the minimum and maximum volumes. This was expected as a result of the potential model under-prediction.

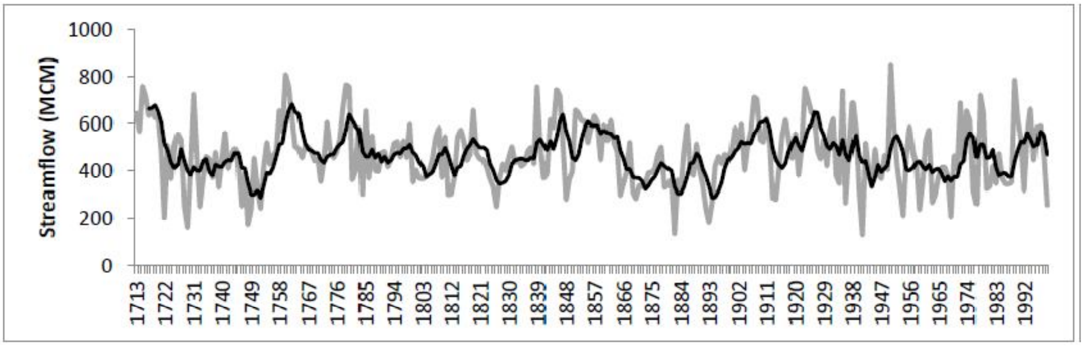
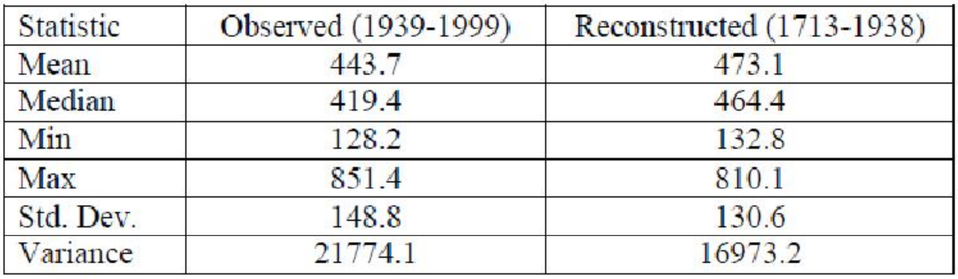


**Figure 3: Reconstructed Streamflow (1713-1999) With 5 Year Running Mean (Solid Black Line)**

**Table 3: Observed Vs. Reconstructed Streamflow (MCM) Statistics**



| Statistic | Observed (1939-1999) | Reconstructed (1713-1938) |
|---|---|---|
| Mean | 443.7 | 473.1 |
| Median | 419.4 | 464.4 |
| Min | 128.2 | 132.8 |
| Max | 851.4 | 810.1 |
| Std. Dev. | 148.8 | 130.6 |
| Variance | 21774.1 | 16973.2 |

The reconstructed and observed periods were then split into 30-year periods for further comparison (Figure 4 and Table 4). Of note is the period 1790-1879 which represented a period of minimal extremes, low variances, and relatively stable mean conditions. The period with the largest variance (19632.9MCM), and hence greatest extremes occurred 1940-1969 during the observed record.

In comparison, the period 1790-1819 which marked the beginning of the stable period experienced a much lower variance of 778.9MCM. All reconstructed periods had higher median streamflow than the observed period initially suggesting a shift in the operation of the Red River Basin hydroclimatological system in line with research by Milly et al. (2008).

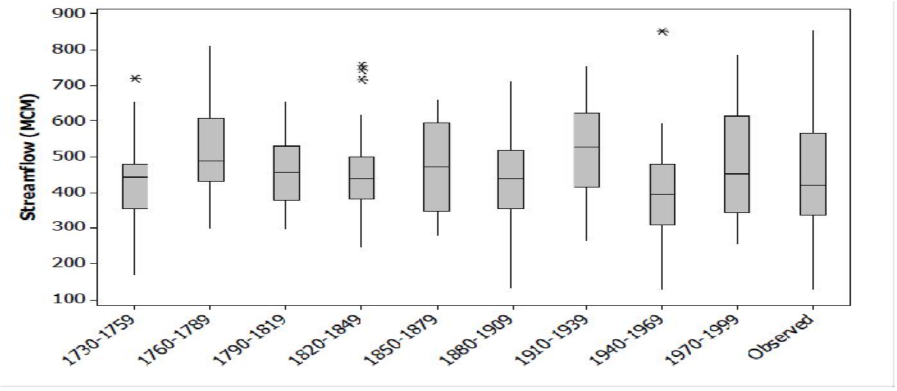
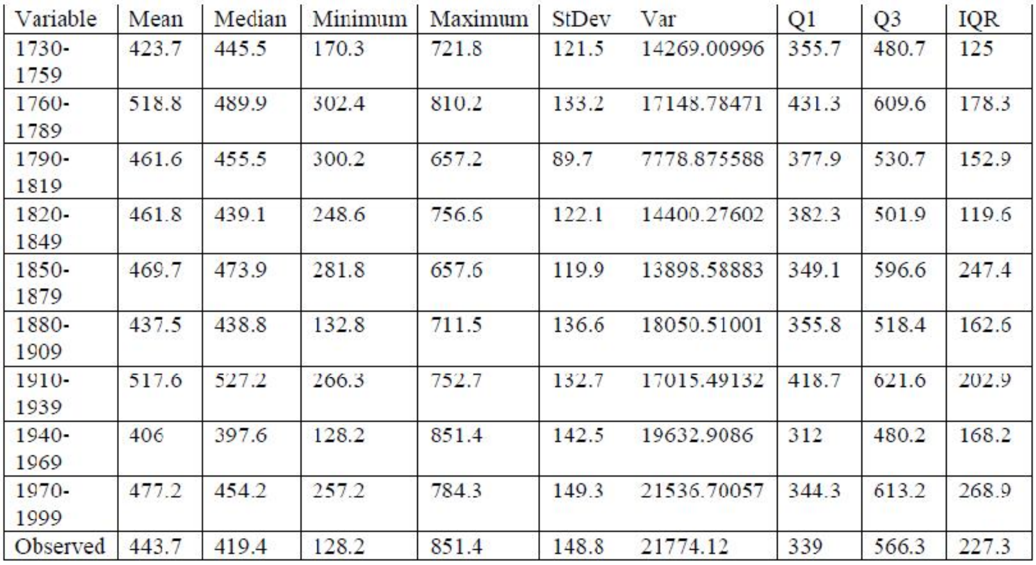


**Figure 4: Boxplots of 30-Year Streamflow for Observed and Reconstructed Periods**

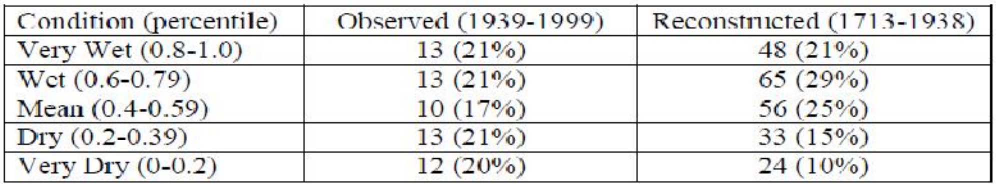
**Table 4: 30-Year Streamflow (MCM) Descriptive Statistics**



| Variable | Mean | Median | Minimum | Maximum | StDev | Var | Q1 | Q3 | IQR |
|---|---|---|---|---|---|---|---|---|---|
| 1730-1759 | 423.7 | 445.5 | 170.3 | 721.8 | 121.5 | 14269.00996 | 355.7 | 480.7 | 125 |
| 1760-1789 | 518.8 | 489.9 | 302.4 | 810.2 | 133.2 | 17148.78471 | 431.3 | 609.6 | 178.3 |
| 1790-1819 | 461.6 | 455.5 | 300.2 | 657.2 | 89.7 | 7778.875588 | 377.9 | 530.7 | 152.9 |
| 1820-1849 | 461.8 | 439.1 | 248.6 | 756.6 | 122.1 | 14400.27602 | 382.3 | 501.9 | 119.6 |
| 1850-1879 | 469.7 | 473.9 | 281.8 | 657.6 | 119.9 | 13898.58883 | 349.1 | 596.6 | 247.4 |
| 1880-1909 | 437.5 | 438.8 | 132.8 | 711.5 | 136.6 | 18050.51001 | 355.8 | 518.4 | 162.6 |
| 1910-1939 | 517.6 | 527.2 | 266.3 | 752.7 | 132.7 | 17015.49132 | 418.7 | 621.6 | 202.9 |
| 1940-1969 | 406 | 397.6 | 128.2 | 851.4 | 142.5 | 19632.9086 | 312 | 480.2 | 168.2 |
| 1970-1999 | 477.2 | 454.2 | 257.2 | 784.3 | 149.3 | 21536.70057 | 344.3 | 613.2 | 268.9 |
| Observed | 443.7 | 419.4 | 128.2 | 851.4 | 148.8 | 21774.12 | 339 | 566.3 | 227.3 |

Regarding the hydrological conditions (wet versus dry), the observed period contained a higher proportion of individual wet years ($\leq 0.2$ percentile), accounting for 41% of the total period versus 35% for the reconstructed period (Table 5). This agrees with the statistics in Table 3 in that the observed period, whilst not experiencing any prolonged extreme wet or dry conditions has certainly experienced a greater proportion of dry years in total. However, the reconstructed period experienced a greater proportion of wetter conditions overall (49%) compared to the observed period (41%). Furthermore, the observed period hydrological conditions are fairly evenly split at approximately 20% each, while the reconstructed period is skewed towards the wetter conditions.

**Table 5: Observed vs. Reconstructed Streamflow Hydrological Conditions**



| Condition (percentile) | Observed (1939-1999) | Reconstructed (1713-1938) |
|---|---|---|
| Very Wet (0.8-1.0) | 13 (21%) | 48 (21%) |
| Wet (0.6-0.79) | 13 (21%) | 65 (29%) |
| Mean (0.4-0.59) | 10 (17%) | 56 (25%) |
| Dry (0.2-0.39) | 13 (21%) | 33 (15%) |
| Very Dry (0-0.2) | 12 (20%) | 24 (10%) |

Figure 5 displays the prolonged (minimum 5 consecutive years) wet and dry periods. Again, no prolonged wet or dry periods occurred during the observed period, but 7 wet and 4 dry periods existed during the reconstructed period suggesting that more inter-annual hydroclimatological fluctuation now exists across the region further agreeing with the higher variance during the observed period. It is important to remember at this stage that these prolonged conditions actually occurred despite potential under-prediction during the reconstructed period by the model again. Figure 6 further supports this by showing the frequency of consecutive wet and dry years for both periods. Again, during the observed period the maximum number of consecutive wet years did not exceed 3, compared to 9 consecutive wet years during the reconstructed period. Similarly the maximum number of consecutive dry years did not exceed 4 during the observed period, compared to 6 during the reconstructed period.

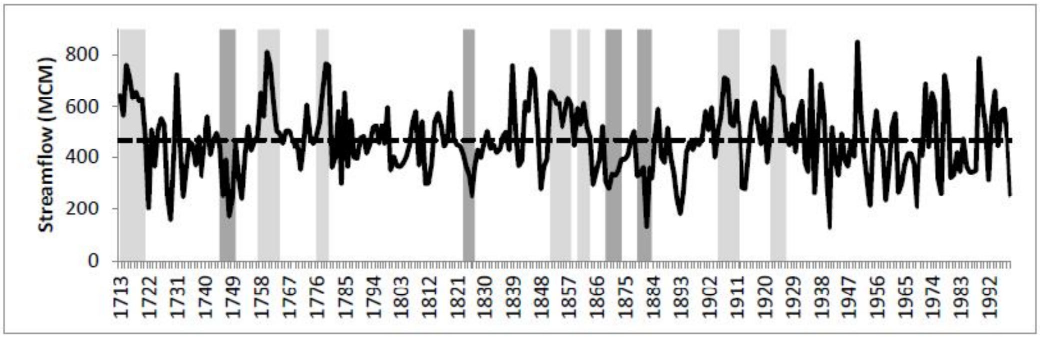


Figure 5: Reconstructed Streamflow (1713-1999) with Prolonged Wet (Light Gray) and Dry (Dark Gray) Periods Highlighted. Mean Streamflow Shown with Hatched Line

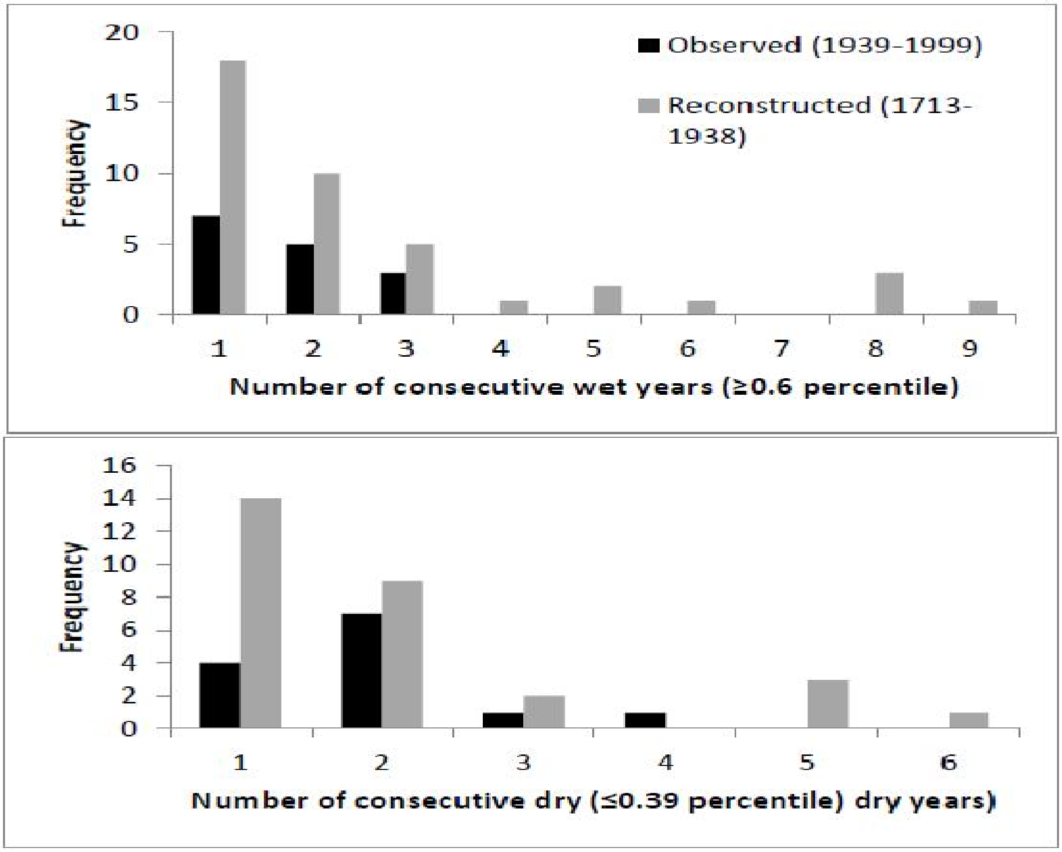


Figure 6: Frequency of Consecutive Wet (Top) and Dry (Bottom) Years for the Observed and Reconstructed Periods

## 5. Conclusions

Dendrochronology has proven to be a valuable tool in reconstructing historical streamflow far beyond the gauged history of many river basins. It provides an extended assessment of the past hydrology and hence climate of the region. Historical data of this nature are a fundamental source of information for water resource planners, flood hazard researchers and river basin ecologists for better understanding challenges that may lie ahead in terms of the future variability of streamflow in response to wetter or drier conditions. Currently these planners and researchers will base their analysis and research on the extremes of hydrological conditions from the gauged history, which may not be an accurate documentation of either the magnitude or frequency of these conditions following an extended reconstruction of streamflow. The basis of this research was to provide an extended streamflow history for a region that is currently lacking this kind of research, yet has displayed a wide range of hydrological extremes over its gauged history and provides a unique habitat for several moisture sensitive plant and tree species. It is apparent from this research that while the more recent observed streamflow record has witnessed a reduction in the number and frequency of extended wet and dry periods, there has been an increase in the extremes of wet and dry conditions. This suggests that the predictability of annual wet and dry conditions is declining in light of the reconstructed data. This could imply a shift in the operation of the hydroclimatological system of the Red River basin with further individual wet and dry extremes possible in the future. This could ultimately result in an increase in short-term flood and drought hazard issues. However, further research should be conducted which incorporates other tree ring chronologies, both internal and external to the basin. This could also include other species to document the historical hydroclimatological record of the Red River Basin to potentially increase the model viability in reconstructing historical streamflow.

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